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RESEARCH ARTICLE

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A modest increase in fire weather overcomes resistance to fire spread in recently burned boreal forests

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Abstract

Recently burned boreal forests have lower aboveground fuel loads, generating a negative feedback to subsequent wildfires. Despite this feedback, short-interval reburns (≤20 years between fires) are possible under extreme weather conditions. Reburns have consequences for ecosystem recovery, leading to enduring vegetation change. In this study, we characterize the strength of the fire-fuel feedback in recently burned Canadian boreal forests and the weather conditions that overwhelm resistance to fire spread in recently burned areas. We used a dataset of daily fire spread for thousands of large boreal fires, interpolated from remotely sensed thermal anomalies to which we associated local weather from ERA5-Land for each day of a fire's duration. We classified days with >3 ha of fire growth as spread days and defined burned pixels overlapping a fire perimeter ≤20 years old as short-interval reburns. Results of a logistic regression showed that the odds of fire spread in recently burned areas were ~50% lower than in long-interval fires; however, all Canadian boreal ecozones experienced short-interval reburning (1981–2021), with over 100,000 ha reburning annually. As fire weather conditions intensify, the resistance to fire spread declines, allowing fire to spread in recently burned areas. The weather associated with short-interval fire spread days was more extreme than the conditions during long-interval spread, but overall differences were modest (e.g. relative humidity 2.6% lower). The frequency of fire weather conducive to short-interval fire spread has significantly increased in the western boreal forest due to climate warming and drying (1981–2021). Our results suggest an ongoing degradation of fire-fuel feedbacks, which is likely to continue with climatic warming and drying.

KEYWORDS

boreal forest, fire spread, fire weather, Forest fire, reburn, short-interval fire, wildfire

1 | INTRODUCTION

The circumpolar boreal biome contains approximately one-third of the world's forests, making it a globally important carbon store (Bradshaw & Warkentin, 2015; Gauthier et al., 2015). Wildfires are the major stand-renewing disturbance across much of the boreal forest (Guindon et al., 2014; Jones et al., 2022), and account for approximately 1.9 Mha of area burned each year in Canada (Hanes

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et al., 2019). Wildfires substantially reduce aboveground and soil biomass for several years, making recently burned areas less likely to burn than would be expected if fire burned randomly across landscapes (Buma et al., 2020; Hart et al., 2019; Héon et al., 2014), due to the lower availability of biomass or fuel for fire (Thompson et al., 2017), as well as the higher foliar moisture content associated with increased broadleaf vegetation prevalent in some young forests (Chen et al., 2009; Cumming, 2001; Hayes & Buma, 2021). Resistance of recently burned areas to fire is particularly strong in the early decades after fire, making the occurrence of 'reburning' at very short intervals (e.g. 1–20 years) relatively rare (Buma et al., 2020; Héon et al., 2014; Parks et al., 2015). Stand-age-mediated resistance to fire spread decays over time as fuel accumulates and the forest reaches the highly flammable conditions associated with mature stands (Beverly, 2017; Buma et al., 2020; Parks et al., 2015).

Warming and drying associated with climate change have increased the prevalence of fire-conducive weather (Jain et al., 2022; Richardson et al., 2022), resulting in fire activity increases across circumpolar boreal forests (Hanes et al., 2019; Jones et al., 2022; Kelly et al., 2013). With more forests burning, the area of early successional or young forests on the boreal landscape has increased (Searle & Chen, 2017; Wang et al., 2020), as well as the proportion of the landscape that may exhibit a negative feedback to fire from young forest fuels. Fire weather strongly controls the likelihood of fire spread and extreme fire behaviour in boreal forests, and severe weather conditions can overcome the resistance provided by bottom-up (i.e. biomass and fuel) constraints (Hély et al., 2001; Wang et al., 2023). Extreme fire weather is regularly implicated in the occurrence of uncontrollable or unexpected wildfire. For example, Foehn winds in California have created large, fast-moving fires, even in areas without extensive fuels (Keeley & Syphard, 2019). In Catalonia, drought and fuel aridity is shown to remove functional barriers to fire spread from landscape heterogeneity, creating connected landscapes where fire activity does not depend on fuels (Duane et al., 2021). Despite the resistance of recently burned areas to fire spread, the occurrence and extent of short-interval reburns in North American forests have also increased alongside overall increases in area burned (Buma et al., 2020, 2022; Whitman et al., 2022). Given the negative feedback, young forests exert on fire activity, the increase in short-interval reburns points to a weakening of this control with worsening fire weather (Erni et al., 2017; Parks et al., 2018).

With the increasing likelihood of short-interval reburning, there has been growing interest in understanding ecological impacts of this phenomenon (Harvey et al., 2023). Many forest ecosystems historically demonstrated a resilient response to wildfire, but shifting disturbance regimes increasingly overwhelm this resilience (Coop et al., 2020; Johnstone et al., 2016). In boreal forests, the post-fire successional trajectory over decades to hundreds of years generally leads to a similar composition and structure to that of the pre-fire forest (Payette, 1992; Walker et al., 2023). Short-interval reburning along with severe fire effects (e.g. reduced availability of viable seeds and altered seedbeds) have been implicated in type conversions of conifer-dominated boreal forests to broadleaf forests and shrublands (Brown & Johnstone, 2012; Hart et al., 2019; Hayes & Buma, 2021; Whitman et al., 2019). Rather than creating temporary changes where forests eventually rebound and recover, changing fire frequencies are contributing to an ongoing shift away from conifer dominance in boreal forests at a continental scale, particularly through a decline of spruce (*Picea* spp.) (Baltzer et al., 2021; Searle & Chen, 2017; Wang et al., 2020).

Despite the increasing prevalence of short-interval reburns in boreal forests and the notable ecosystem changes they produce, the weather conditions that enable fire to spread in recently burned areas have not been well documented. The goal of this research is to characterize the strength with which recently burned areas resist fire spread, and the shifting occurrence of the weather conditions that overwhelm this resistance. For the boreal ecozones of Canada we sought to:

1. Quantify the difference in short- and long-interval fire spread likelihood;
2. Quantify the difference between fire weather conditions during short- and long-interval fire spread;
3. Identify fire-weather thresholds beyond which the resistance of recently burned areas to fire spread is overcome; and,
4. Characterize regional patterns of short-interval reburn occurrence and long-term trends in the fire weather conditions associated with short-interval fire spread.

Our results will improve understanding of the factors that overwhelm resistance to burning in recently burned areas and provide insight as to when recently burned areas can continue to serve as fire breaks for communities. By linking short- and long-interval fire likelihood to daily fire weather, this analysis can assist in the parameterization of models for fire-catalysed forest conversions and future carbon balance.

2 | MATERIALS AND METHODS

2.1 | Data

To meet these research objectives, we used the Canadian Fire Spread Dataset (CFSDS) of daily area burned (Barber et al., 2024). The CFSDS consists of daily fire progression maps interpolated from satellite-detected thermal anomalies ("hotspots") from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors (2002–2021), following the methods of Parks (2014). The dataset consists of rasters (180-m resolution) of interpolated day of burning within all mapped fire perimeters of a final size ≥1000 ha (Skakun et al., 2022). Fire perimeters in this dataset exclude unburned islands, mapping only areas that actually burned. An example of interpolated daily fire spread is shown in Figure S1. All data processing and statistical analysis took place in the R environment (R Core Team, 2023).

For each burned area, we extracted daily local weather from the ERA5-Land reanalysis product, which is produced hourly at

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0.1° spatial resolution (~9 km; Muñoz-Sabater et al., 2021). This included maximum daily temperature (T_{max};°C), maximum daily vapour pressure deficit (VPD; hPa), noon temperature (T;°C), noon relative humidity (RH; %), noon wind speed (km h^{-1}), and 24-h precipitation accumulated to local noon each day. Using the noon weather from ERA5-Land, we calculated the daily indices of the Canadian Fire Weather Index (FWI) System: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Buildup Index (BUI), Initial Spread Index (ISI), and FWI (Van Wagner, 1987). To account for inter-seasonal moisture deficits, we used an overwintering procedure where the FWI System calculation was started when ERA5-Land snow cover was below 50% for three consecutive days, thereby defining the fire season window (Barber et al., 2024). FWI System indices are unitless and increase in value with increasing fire weather severity. Daily fire weather indices derived from the ERA5 reanalysis are highly correlated to observed weather at weather stations in Canada (Spearman's $|\rho|>.7$), although they have a negative bias. This bias is pervasive but is most pronounced south of the boreal forest, particularly in southern Alberta (McElhinny et al., 2020). The ERA5-Land dataset employed here is a finer-scale replay of the land component of ERA5. It is documented that weather reanalysis products may not reproduce extremes observed in measured weather data (Field, 2020). Using noon weather and winds at a 0.1° resolution, we may not be able to resolve wind events that drive fire spread due to diverse topography or fire-weather interactions. We pooled the fires from the Prairies ($n=7$ fires) and Boreal Plains ecozones ($n=350$ fires), and excluded all other fires that burned outside of the boreal forest ecozones (Ecological Stratification Working Group, 1995). This produced a dataset of 2941 unique fires for analysis (Table S1).

To represent fuels, we extracted pre-fire vegetation attributes for every burned 180-m CFSDS pixel from the nearest pre-fire year of the Spatialized CAnadian National Forest Inventory (SCANFI; Guindon et al., 2023, 2024). We also extracted the likelihood of peatland (peat-forming wetland) presence within each pixel (Thompson et al., 2016). To identify short-interval reburns, we recorded the age of any prior fire overlapped by a CFSDS pixel in categories of ≤10, ≤15, ≤20 and ≤30 years prior to the fire year of interest, using fire perimeters from the Canadian National Fire Database (CNFDB; 1985–1972; Natural Resources Canada, Canadian Forest Service, 2023) and the National Burned Area Composite (NBAC; 1986–2020; Skakun et al., 2022). An example of daily fire spread in relation to historical fire perimeters is shown in Figure S1. This associated pre-fire fuels and fire intervals to all burned areas of each CFSDS fire. To examine differences in pre-fire fuels between fire intervals, we averaged the pre-fire fuel characteristics for each day of burning for each fire separately for recently burned areas and long-interval fires, producing a dataset henceforth referred to as the 'pre-fire fuel dataset'.

To examine the weather conditions during fire spread, we summarized daily weather by taking the mean for all pixels burned on a given day and the associated total daily area burned per fire. The summarized daily data is henceforth referred to as the 'fire spread dataset'.

We classified the fire spread dataset into spread days and non-spread days. We considered days when ≥3.24 ha burned (henceforth '3 ha' for simplicity; area of one 180-m pixel) a fire-spread day. When a fire was not yet extinguished, but there were no hotspots outside of already burned areas (days with no fire growth, between spread days), we introduced observations of non-spread days. For non-spread days, we extracted the day's weather within the extent of the next burning day's area, that is, the area that failed to burn during the non-spread day. We assigned zero hectares burned to such days.

If the daily burned area overlapped a fire perimeter that burned in a previous year, we recorded the fire interval of each overlap in categories of ≤10, ≤15, ≤20 and ≤30 years between fires, as described above. Non-spread days were assigned a fire interval based on the fire interval of the subsequent spread day. For example, if the fire ceased growing adjacent to a recently burned area, which subsequently burned over, the non-spread day would be assigned this same fire interval. We classified all spread and non-spread days without any overlaps as long-interval fire. We then created a balanced dataset with equal numbers of spread and non-spread days for each ecozone (Table S1) with random downsampling using the *caret* package (Kuhn, 2008).

2.2 | Analysis

We used the fire spread dataset for the entire Canadian boreal biome to quantify the strength of the resistance of recently burned areas to fire spread. We provide a list of predictor variables used to describe pre-fire fuels and explain the likelihood of fire spread in Table 1. We created a multivariable logistic regression generalized mixed-effect model (GLMM) with a random effect of fire ID to explain fire spread probability as a function of two daily weather variables with relatively low levels of correlation (Spearman's $|\rho|<.7$), and a categorical variable indicating whether the area was recently burned in four fire interval classes (≤10, ≤15, ≤20 and ≤30 years between fires), or older forest (i.e. short- and long-interval fire). We included an offset term of the prior day's area burned to control for the bias of large fires being more likely to encounter previously burned areas. We fitted all GLMMs using the *lme4* package (Bates et al., 2015) and calculated pseudo-R^2 values for each model with the *MuMIn* package using the theoretical variance method for binomial distributions (Bartoń, 2023). We compared the strength of the resistance of recently burned areas to fire spread between the four fire interval classes in the GLMMs, as well as the sample size of short-interval spread days. From these results, we defined areas that burned with ≤20 years between fires as short-interval reburns for all further analysis (Table 2). We then calculated Vargha-Delaney effect size measures for the strength of the effect of weather on determining whether a day was a spread or non-spread day, using the *effsize* package (Torchiano, 2020). We excluded any weather variables that had a negligible effect on overall fire spread from further modelling and analysis. Subsequent analyses were conducted at the level of individual ecozones.

To characterize fuel conditions and the presence of peatlands prior to short- and long-interval fire spread, we tested for significant

TABLE 1 Predictor variables considered in models of daily fire spread, and assessment of pre-fire fuels.

Predictor variable	Abbreviation	Units	Range	Data source	References
Maximum temperature	T_{max}	°C	0–38	ERA5-Land	Muñoz-Sabater et al. (2021)
Maximum vapour pressure deficit	VPD	hPa	1–51	ERA5-Land	Muñoz-Sabater et al. (2021)
Noon relative humidity	RH	%	15–100	ERA5-Land	Muñoz-Sabater et al. (2021)
Fine Fuel Moisture Code	FFMC	Unitless	0–95	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Duff Moisture Code	DMC	Unitless	0–172	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Drought Code	DC	Unitless	4–733	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Buildup Index	BUI	Unitless	0–200	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Initial Spread Index	ISI	Unitless	0–48	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Fire Weather Index	FWI	Unitless	0–77	ERA5-Land	Muñoz-Sabater et al. (2021) Van Wagner (1987)
Aboveground biomass	Aboveground biomass	T/ha	1–224	SCANFI	Guindon et al. (2023, 2024)
Proportion aboveground biomass from conifer	% Conifer	%	3–100	SCANFI	Guindon et al. (2023, 2024)
Canopy closure	Canopy closure	%	0–90	SCANFI	Guindon et al. (2023, 2024)
Probability of treed or forested peatland	Peatland probability	%	4–92	Distribution of forested peatlands in Canada map product	Thompson et al. (2016)

TABLE 2 Results of individual generalized linear mixed-effects logistic regression models (Equation 1) for each of four possible age class definitions of short-interval reburning, predicting the likelihood of daily fire spread in the Canadian boreal biome. We report the fixed effects, alongside their odds and the conditional and marginal pseudo-R^2.

SFI age class	Variable	β(logit)	SE	Odds ratio	p	Marginal pseudo-R^2	Conditional pseudo-R^2
≤10 years between fires	Intercept	−4.70	.18	–	<.001	.36	.50
	FFMC	.08	.002	1.08	<.001		
	RH	−.04	.002	0.96	<.001		
	SFI	−.73	.06	0.48	<.001		
≤15 years between fires	Intercept	−4.70	.19	–	<.001	.36	.50
	FFMC	.08	.002	1.08	<.001		
	RH	−.04	.002	0.96	<.001		
	SFI	−.62	.05	0.54	<.001		
≤20 years between fires	Intercept	−4.63	.19	–	<.001	.36	.50
	FFMC	.08	.002	1.08	<.001		
	RH	−.04	.002	0.96	<.001		
	SFI	−.63	.04	0.53	<.001		
≤30 years between fires	Intercept	−4.67	.19	–	<.001	.36	.50
	FFMC	.08	.002	1.08	<.001		
	RH	−.04	.002	0.96	<.001		
	SFI	−.63	.04	0.53	<.001		

Abbreviations: FFMC, Fine Fuel Moisture Code; RH, relative humidity; SFI, Short fire interval.

differences in pre-fire fuels and peatland likelihood in the pre-fire fuel dataset, using bootstrapped two-sided studentized Wilcoxon tests in the *nptest* package (Helwig, 2023).

We summarized the annual average area burned, area reburned, and proportion reburned of all large fires (≥200 ha; 1981–2021). We used the CNFDB (Natural Resources Canada,

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Canadian Forest Service, 2023) (CNFDB; 1961–1985) and NBAC (Skakun et al., 2022) (1986–2021) to map short-interval reburned areas, calculated in the 20 years prior to a fire year of interest. To render the two fire-perimeter datasets comparable over this time period, for this analysis only, we filled unburned islands in fire perimeter polygons and then removed waterbodies (1 M scale; Natural Resources Canada, 2023). We rasterized the maps of fire perimeters at a 180-m resolution and identified short-interval reburn overlaps (≤20 years between fires) in the *terra* package (Hijmans, 2023). We calculated ecozonal means of the area that experienced short-interval reburns and identified the 90th percentile annual area reburned and annual % area reburned from the 41-year time series.

We tested for significant differences in daily fire weather between short- and long-interval spread days using one-sided bootstrapped studentized Wilcoxon tests. To determine whether the occurrence of extreme weather necessary for reburning has increased over time, we fitted bivariate logistic GLMMs of short-interval fire spread likelihood using each weather variable of interest and subsequently predicted threshold weather conditions beyond which (above or below) there was a high likelihood of fire spread in recently burned areas; henceforth referred to as 'reburning weather days'. For this analysis we used short-interval spread days only and then further downsampled non-spread days to re-balance the dataset. We identified probability breakpoints for short-interval fire spread for each combination of ecozone and weather variables using the Youden index (Youden, 1950), calculated with the *cutpointr* package (Thiele & Hirschfeld, 2021). In cases where the reburning weather probability threshold identified with the Youden index was below a 50% spread likelihood, we substituted a probability threshold of 0.51 to ensure thresholds indicated conditions where short-interval fire spread was more likely than not.

To analyse changes in the occurrence of reburning fire weather days over time, we calculated the annual number of reburning weather days per-pixel from 1981 to 2021 in the ERA5-Land dataset and reported the mean number of reburning weather days for this period. We also calculated the 90th percentile of the yearly number of reburning weather days for the time series (or approximately a 1-in 10-year fire weather event) and the average in each pixel. Finally, we used annual grids to identify trends in pixel-level Sen's slopes for the number of reburning weather days and fire season length. We determined the significance of trends ($\alpha = .1$) for all pixels using two-sided Mann-Kendall trend tests corrected for temporal autocorrelation (Zhang et al., 2000), calculated using the *spatialEco* package (Evans & Murphy, 2021). We produced figures showing results using the *tidyverse* (Wickham et al., 2019), *sjPlot* (Lüdecke, 2023) and *cowplot* (Wilke, 2020) packages, and QGIS (QGIS Association, 2020).

3 | RESULTS

Recently burned areas in the Canadian boreal forest significantly resist fire spread. In our generic logistic GLMMs of balanced datasets from the entire boreal biome, using daily fire spread data from 2923 large boreal forest fires (≥1000 ha) (Equation 1) (Table 2), the odds of short-interval fire spread were 46%–52% lower relative to long-interval fire spread, after accounting for the effects of weather and the prior day's growth in hectares (Table 2). Young forests ranging in age from 10 to 30 years offer similar resistance to fire spread (Table 2), with the strongest resistance to fire spread in the first 10 years after fire. For subsequent analyses, we report results using an interval of ≤20 years between fires to define short-interval reburns due to the similarity of the effect in these models and the larger dataset size afforded with the ≤20-year cutoff. As the severity of fire weather increases, the difference in the probability of short- and long-interval fire spread declines (Figure 1)

$$\mathrm{logit}(P\ \mathrm{Fire\ Spread}) = \log_{10}(\mathrm{PAB}+1) + \beta_0 + \beta_1\mathrm{FFMC} + \beta_2\mathrm{RH} + \beta_3\mathrm{SFI} + \beta_4(1|\mathrm{FireID}). \tag{1}$$

Fire spread is a dichotomous variable (0, 1), with 1 indicating any fire spread. Short fire interval (SFI) is a categorical variable (0,1) with SFIs (classes of ≤10, 15, 20 and 30 years between fires) indicated by 1 and long intervals indicated by 0. Previous area burned is an offset term of the logarithm of the previous day's area burned (ha). FireID is a categorical variable with a unique identifier for each fire, included as a random effect. Model coefficients are reported in Table 2.

All ecozones have significant differences in pre-fire fuels ($p \le .05$) between short-interval and long-interval burned areas, which

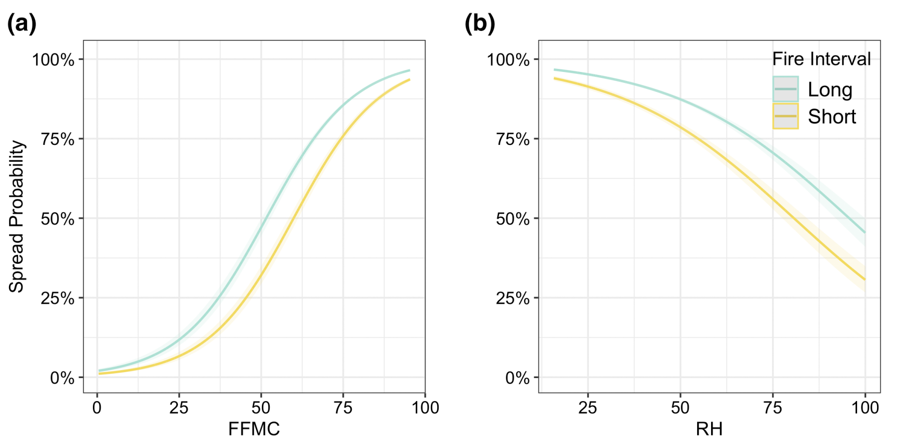

FIGURE 1 Marginal effect plots of the probability of short- and long-interval fire spread, as a function of daily fire weather (a) Fine Fuel Moisture Code (FFMC), and (b) relative humidity (RH; %) in a logistic generalized linear mixed-effect model, with short-interval fire spread defined as ≤20 years between fires (Equation 1; Table 2).

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supports the assertion that recently burned areas have less aboveground fuel than neighbouring older forests (Figure S2c,d). Short-interval reburns were more likely to have occurred in uplands than peatlands, in comparison to long-interval burned areas, in all ecozones (Figure S2a). Pre-fire conifer dominance prior to short- versus long-interval fire spread varied between ecozones, with some pre-reburn fuels having a significantly higher proportion of pre-fire aboveground biomass from conifers (e.g. in the Taiga Cordillera, Boreal Cordillera, Taiga Plain, Taiga Shield East and Boreal Shield East), whereas in the Boreal Shield West recently burned areas had significantly less conifer biomass than surrounding older forests that burned (Figure S2b).

Daily weather and FWI System indices had a meaningful effect on short- and long-interval fire spread (Figure 2; Table S2). Noon wind speed (km h^{-1}) and DC had negligible effects on whether a fire spread day occurred, and therefore, we did not consider them for further analyses (Table S2). Fire spread days were significantly drier and/or warmer than non-spread days in all ecozones, in both short- and long-interval fire spread (Tables S2–S4). Fire weather during short-interval fire spread was significantly more extreme than fire weather during long-interval fire spread (Figures 2 and 3). RH was significantly lower, and FFMC, DMC and FWI were significantly higher on short-interval spread days than long-interval spread days in all ecozones, whereas T_{max}, VPD, BUI and ISI were significantly higher during short-interval fire spread only in certain ecozones (Figure 3). We identified reburning weather thresholds for all fire weather variables with non-negligible effects on fire spread from bivariate logistic regression mixed-effect models of short-interval fire spread likelihood (Figure 4). Predictors of FFMC, ISI and FWI performed best in models of short-interval fire spread likelihood, followed by RH, DMC and BUI, with T_{max} and VPD generally being the least predictive (Tables S5–S13). To examine trends in the occurrence of reburning weather days over time, we selected two weather variables that best predicted short-interval fire spread from amongst those that had large Vargha-Delaney effects (Table S2). First, we selected the FFMC for time series analysis, as the FFMC logistic GLMMs had the largest marginal pseudo-R^2 in eight of the nine ecozones. We then eliminated the ISI and FWI from further consideration as they are highly correlated with FFMC (Spearman's $|\rho|>.9$). Of the remaining orthogonal weather variables RH was the best predictor of short-interval fire spread in seven of the nine ecozones.

Northern ecozones typically experienced fewer reburning weather days and shorter fire seasons than southern ecozones, resulting in a reduced prevalence of actual area reburned in these regions relative to the south (Table 3; Figure 5a,b). Reburning weather days were particularly prevalent in the Boreal Plains, Boreal Shield West and Hudson Plains (Table 3; Figure 5). On average, reburning days made up between 4% and 14% of the fire season; however, 90th percentile weather conditions (derived from the annual number of reburning weather days 1981–2021) could result in up to 19% of the fire season consisting of reburning days in the Boreal Plains (Table 3). Short-interval reburns are a small proportion of total area burned in all ecozones, with typical years consisting of 1.4% to 7.9% of the area burned from a short-interval fire. Nationally, an annual average of 108,0115 ha reburns in the Canadian boreal forest (Hudson Plain excluded due to data limitations); however, a single ecozone may have a total area reburned more than double this value in extreme years. For example, the Taiga Plains experienced 275,958 ha of short-interval reburn in 1995, a year when the national total was 532,467 ha reburned.

We found significant trends over time in the frequency with which reburning weather day thresholds were exceeded (Figure 5e,f).

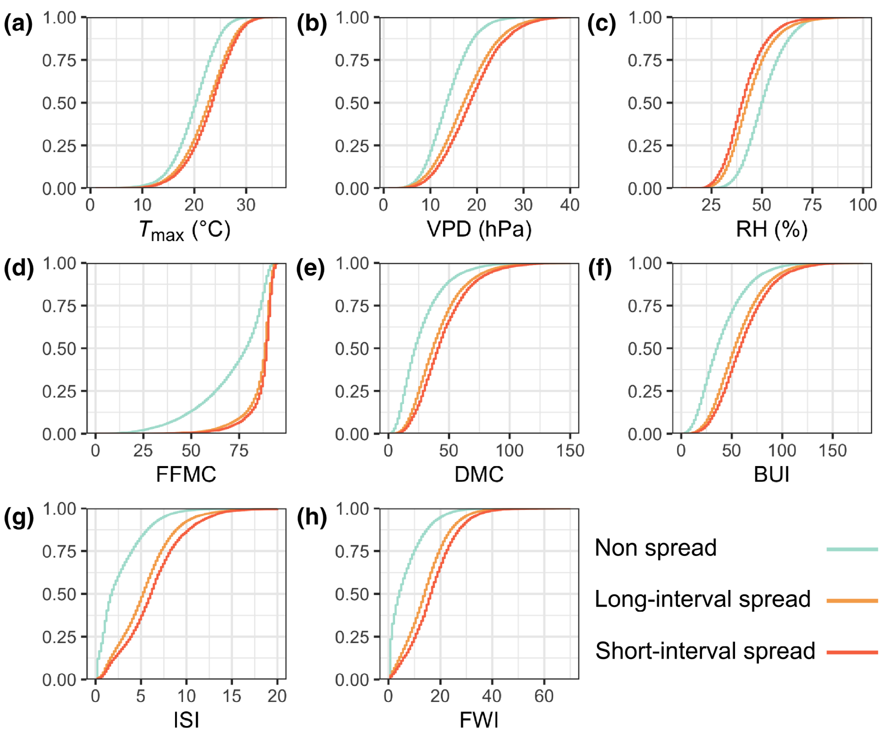

FIGURE 2 Empirical cumulative distribution functions of daily weather during short- and long-interval fire spread and non-spread days. Weather variables shown are (a) maximum temperature (T_{max}), (b) vapour pressure deficit (VPD), (c) relative humidity (RH), (d) Fine Fuel Moisture Code (FFMC), (e) Duff Moisture Code (DMC), (f) Buildup Index (BUI), (g) Initial Spread Index (ISI) and (h) Fire Weather Index (FWI).

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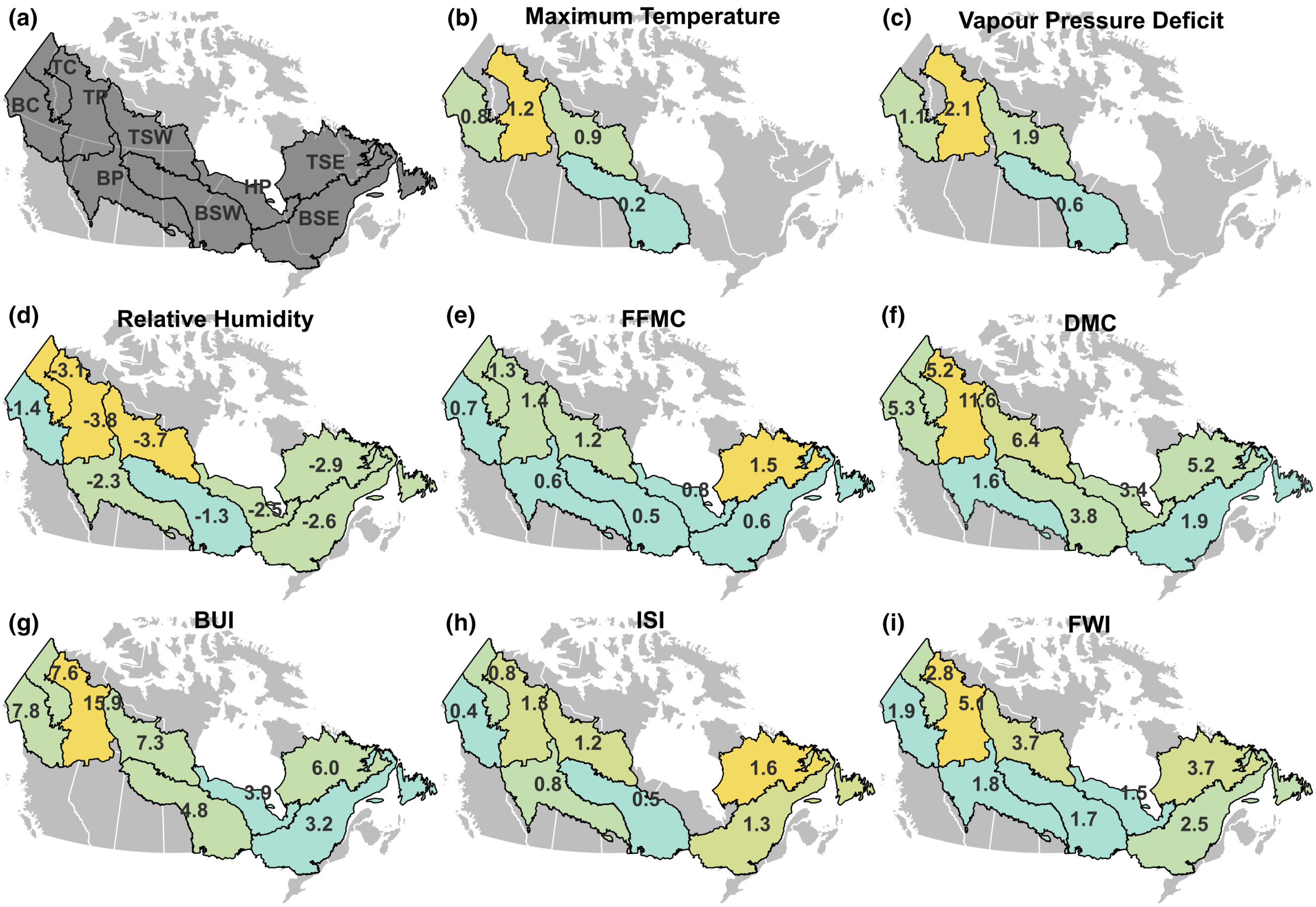

FIGURE 3 Medians of differences between short- and long-interval spread day fire weather within (a) Canadian boreal forest ecozones. Ecozones displayed are the Taiga Cordillera (TC), Boreal Cordillera (BC), Taiga Plains (TP), Boreal Plains (BP), Taiga Shield West (TSW), Boreal Shield West (BSW), Hudson Plains (HP), Taiga Shield East (TSE), and Boreal Shield East (BSE). Weather variables displayed are: (b) maximum temperature (°C), (c) vapour pressure deficit (hPa), (d) relative humidity (%), (e) Fine Fuel Moisture Code (FFMC), (f) Duff Moisture Code (DMC), (g) Buildup Index (BUI), (h) Initial Spread Index (ISI), and (i) Fire Weather Index (FWI). Ecozones displayed have significant differences in daily weather between short- and long-interval fire spread days. Colours correspond to the difference in weather conditions between short- and long-interval spread days, with blue indicating a smaller difference and yellow indicating a greater difference.

The annual number of reburning weather days has increased over some regions of boreal Canada, predominantly in the northwest. The number of reburning weather days (RH threshold) has significantly increased over 58.2 Mha (10.2% of all mapped areas; Figure 5), whereas the number of reburning weather days has significantly decreased over 6.9 Mha (1.2%). Similarly, when derived from the FFMC threshold, the number of reburning weather days has significantly increased over an area of 43.2 Mha (7.5% of mapped area), as opposed to significant declines over only 2.9 Mha (0.5%; Figure 5). Significant increases in the occurrence of reburning weather days were concentrated in the Boreal and Taiga Cordillera, as well as the Boreal and Taiga Plains ecozones. When examined within only these four westernmost ecozones, the frequency of days with extreme fire weather conducive to short-interval fire spread has significantly increased in 26.0% (RH threshold) and 15.3% (FFMC threshold) of the region. Increases in the number of reburning weather days occurred alongside a significantly lengthening fire season over most of northern Canada (490.2 Mha with significant increases in fire season length; Figure S3).

4 | DISCUSSION

We offer evidence pointing to a fire-fuel feedback throughout the Canadian boreal biome. Recently burned areas of boreal forests significantly reduce the odds of fire spread by approximately 50% relative to long-interval spread. Recently burned areas had a lower likelihood of fire spread than mature forests for at least 30 years; however, the strongest resistance to spread was found in stands that had burned in the past 10 years, which is congruent with findings from other ecosystems (e.g. Buma et al., 2020, 2022; Parks et al., 2015, 2016). The deficiency of fuel in young forests regenerating after a fire in the North American boreal biome presents a limitation to fire activity that could persist for decades, particularly in low-productivity stands (Buma et al., 2020; Héon et al., 2014; Thompson et al., 2017). Fires in this study area reduced the aboveground fuel load for at least 20 years. Prior to reburning, recently burned areas in Canadian boreal forests were fuel-limited, with less aboveground biomass and greater canopy openness (a proxy for canopy fuel load in some western boreal forests; Cameron

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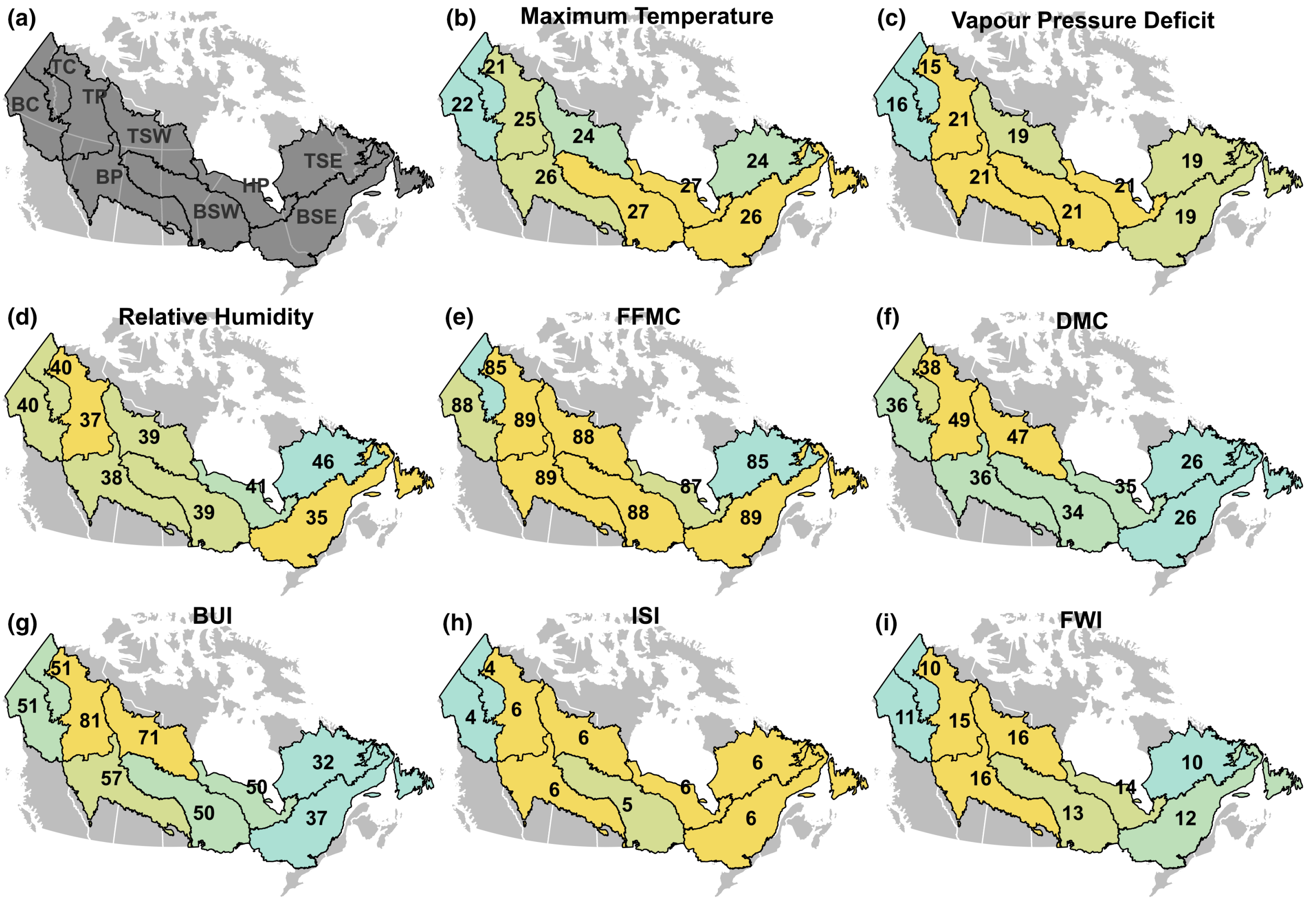

FIGURE 4 Thresholds for reburning weather days within (a) Canadian boreal forest ecozones. Ecozones displayed are the Taiga Cordillera (TC), Boreal Cordillera (BC), Taiga Plains (TP), Boreal Plains (BP), Taiga Shield West (TSW), Boreal Shield West (BSW), Hudson Plains (HP), Taiga Shield East (TSE), and Boreal Shield East (BSE). Weather variables displayed are: (b) maximum temperature (°C), (c) vapour pressure deficit (hPa), (d) relative humidity (%), (e) Fine Fuel Moisture Code (FFMC), (f) Duff Moisture Code (DMC), (g) Buildup Index (BUI), (h) Initial Spread Index (ISI) and (i) Fire Weather Index (FWI). Colours correspond to the weather threshold values, with blue indicating a lower threshold and yellow indicating a higher threshold relative to fire weather severity.

et al., 2021), as well as being generally conifer-dominated, relative to the fuel conditions present prior to long-interval fire. This tendency towards conifer dominance prior to reburning may point to a greater susceptibility to reburning in these sites than in young forests where broadleaf trees prevailed in the post-fire cohort, as young forests that successfully resisted fire spread (did not reburn) are inherently absent from this dataset.

Boreal peatlands are peat-forming wetlands with vast carbon reserves characterized by thick organic soil layers (≥40 cm). Although peatlands regularly burn, their higher water tables generally make them less fire-prone than surrounding uplands (Bourgeau-Chavez et al., 2022; Thompson et al., 2019; Turetsky et al., 2015). Short-interval reburns occurred more often in areas that had a low likelihood of being a peatland (i.e. occurring mostly in drier uplands), as has also been shown in US temperate conifer forests (Buma et al., 2020; Parks et al., 2018). When peatlands do reburn, they experience more limited vegetation community changes than in drier sites (Hayes & Buma, 2021; Whitman et al., 2019), indicating they are both less susceptible to short-interval reburning and less likely to experience dramatic ecological changes as a result (Hoecker et al., 2020).

We observed non-negligible area reburned in all Canadian boreal ecozones. In the 1981–2021 period, boreal ecozones of Canada experienced a baseline condition of 4 to 23 days per fire season with fire weather conditions that met or surpassed weather thresholds that allow short-interval fire spread to occur ('reburning weather days'). Although these days are infrequent and make up a small proportion of the fire season, a few days of severe fire weather and extreme fire spread can dramatically alter the area burned (Coop et al., 2022; Wang et al., 2023), especially when large fires are already burning (Erni et al., 2017). Furthermore, in extreme years (approximately a 1- in 10-year fire season), nearly a quarter of the fire season consists of reburning weather days in some ecozones.

Despite the observed lower fuel loads and associated resistance to fire spread in recently burned areas, our results suggest that a modest increase in fire weather promotes a high likelihood of fire spread, regardless of time since fire. Under extreme fire weather conditions, the difference between the probability of short- and

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TABLE 3 Number of reburning weather days derived from relative humidity (RH) and Fine Fuel Moisture Code (FFMC) thresholds, and area reburned in boreal ecozones. The mean value of the number of reburning weather days and the average fire season length (1981–2021) for each ecozone are reported, alongside the ecozonal mean of the 90th percentile number of reburning weather days in a fire season, in parentheses. The average annual area reburned (≤20 years between fires) is reported for the same period, as well as the total area reburned in 90th percentile years, in parentheses. Area reburned statistics for the Hudson Plains are not reported due to data limitations.

	Number of reburning days (RH threshold)	Number of reburning days (FFMC threshold)	Fire season length	Annual area of short-interval reburn	
Ecozone	Days	Days	Days	Ha	Mean annual % of area burned
Taiga Cordillera	4.0 (9.0)	10.5 (19.1)	98.2 (116.8)	1402 (2646)	2.5
Boreal Cordillera	10.0 (18.1)	10.1 (19.6)	112.6 (131.0)	4912 (18,879)	4.3
Taiga Plains	9.6 (16.8)	9.7 (17.8)	130.2 (146.4)	14,781 (16,706)	3.5
Boreal Plains	22.8 (36.1)	18.9 (32.4)	170.3 (187.7)	18,957 (53,084)	7.1
Taiga Shield West	8.4 (15.0)	10.3 (18.6)	116.3 (133.2)	11,062 (31,310)	3.7
Boreal Shield West	18.1 (28.4)	18.9 (29.9)	157.1 (175.7)	47,838 (114,854)	7.9
Hudson Plains	15.7 (24.0)	17.9 (27.7)	142.6 (161.5)	—	—
Taiga Shield East	9.1 (15.6)	11.8 (19.4)	112.4 (131.4)	2968 (7724)	1.4
Boreal Shield East	7.7 (13.4)	10.9 (18.5)	153.9 (172.1)	6195 (15,069)	4.6

long-interval fire spread dissipates. Anthropogenic climate change is likely to increase the occurrence of short-interval reburning due to the key role of fire weather, particularly aridity, in overcoming recently burned area resistance to fire spread. We report a difference in RH of only −2.6% between short- and long-interval spread days and an FWI 2.5 higher (differences averaged across all ecozones). Global projections of RH suggest that declines of 2%–5% are likely over much of the boreal biome by the 2081–2100 period (Douville & Willett, 2023), alongside an up to 50-day increase in the yearly number of days with a moderate FWI of 11 or higher (Lund et al., 2023). With only a modest difference in weather conditions, the likelihood of short-interval fire spread substantially increased, indicating the possibility of nonlinear responses or threshold behaviour, such as that observed in the relationship of area burned to temperature and aridity (Abatzoglou et al., 2021; Young et al., 2017). It is therefore plausible that these projected increases in fire weather could erode the mechanism by which age-limitation controls the likelihood of fire spread.

Canada has already warmed by 1.9°C since 1948, with temperatures increasing at double the mean global rate, and polar regions warming even more intensely (Environment and Climate Change Canada, 2023). Concurrently, western boreal Canada has experienced drying trends (Jain et al., 2022; Whitman et al., 2022), resulting in a significant increase in the number of reburning weather days reported here across between 15% and 26% of the western boreal forest.

This combination of ongoing warming and drying has produced extreme fire seasons like that of 2023, where extensive areas burned and severe fire weather led to widespread occurrences of short-interval fire in Canadian boreal forests. Although area burned increases are projected to continue with a warming and drying climate (Wang et al., 2022), it is anticipated that fire-fuel feedbacks from the lower fuel load and flammability of recently burned areas will dampen future climate-induced increases in area burned (Gaboriau et al., 2023; Marchal et al., 2020). As the occurrence of extreme years and the number of reburning weather days will likely increase under continued climate warming, the strength and duration of this effect are somewhat uncertain. Together, increasingly severe weather and growing annual area burned point to decreasing strength of fire-fuel feedbacks. This said, repeated reburning (i.e. >2× burned) has compounding effects on post-fire vegetation communities that reinforce the reduced flammability of young forests such as an increasing prevalence of shrubs and broadleaves and fuel gaps (Hayes & Buma, 2021), which may serve to offset increasingly extreme fire weather, following a period of extensive burning.

4.1 | Limitations

We represented fire spread probabilistically using a binary definition of spread, which required the identification of fire spread and non-spread days. We used a minimum area burned of 3 ha (the area of a 180-m pixel) to determine a fire spread day. Using this definition along with the interpolation of satellite thermal anomalies (hotspots), it is possible that days with limited fire growth that produced no detectable hotspots may have been misclassified as non-spread days (false negatives). By identifying non-spread days as days with no hotspot detections outside of previously burned areas, we exclude from consideration areas outside of the final fire perimeter that may have meaningfully resisted fire spread. This represents a potential omission in the dataset of non-spread days. Hotspot detection efficiency is limited by the resolution of the detecting sensor, which is 375 m for VIIRS and 500 m for MODIS. We also assigned a minimum mapping unit of 3 ha for a possible reburn event. This is a fairly small

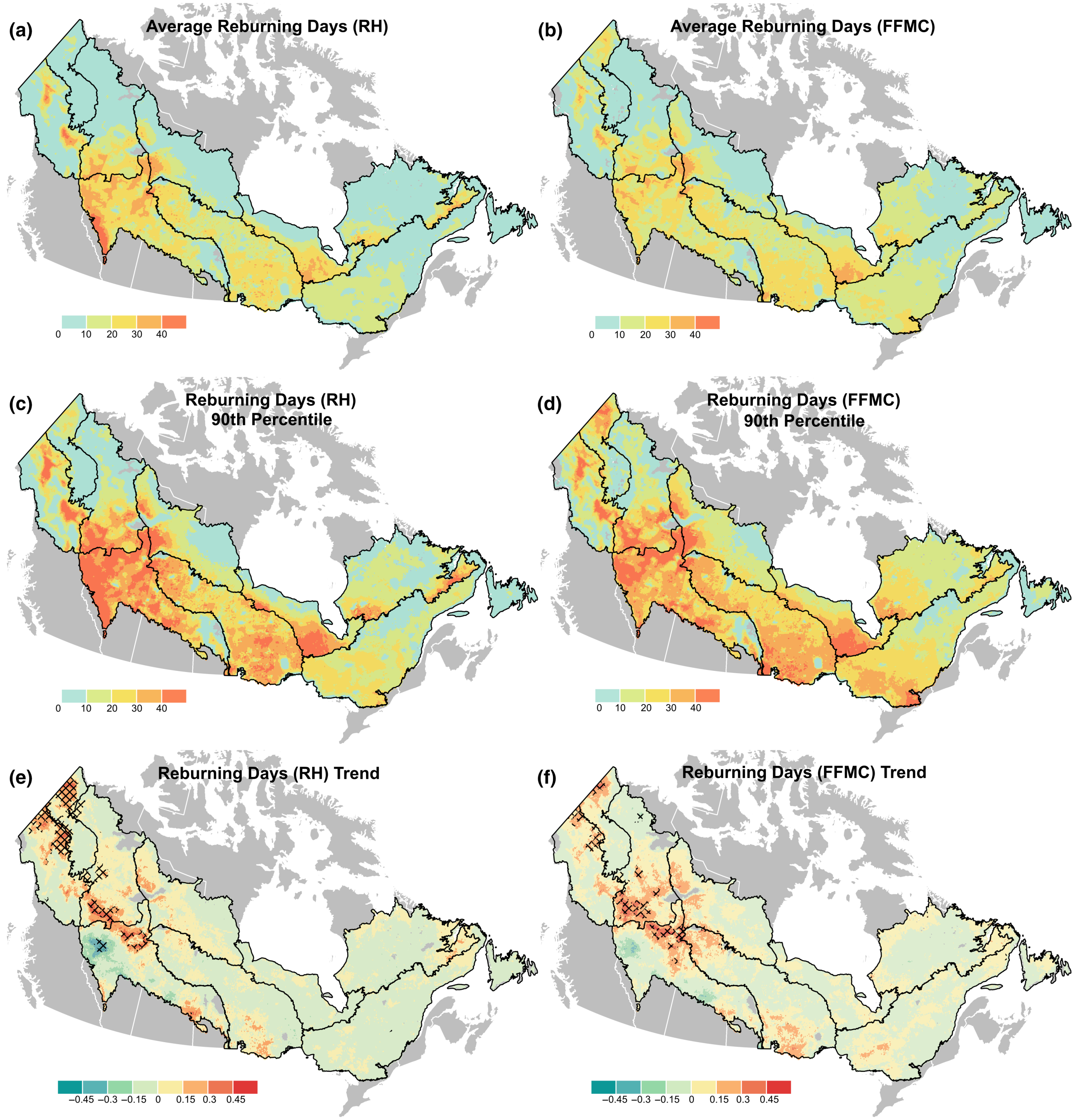

FIGURE 5 Average (a, b) number of reburning weather days in a fire season, 90th percentile (c, d) number of reburning weather days in a fire season and trends (e, f) in the annual number of reburning weather days (1981–2021). Days with extreme weather conducive to reburning were identified using Relative Humidity (RH; a, c, e) and Fine Fuel Moisture Code (FFMC; b, d, f) reburning weather thresholds. Trends are represented by Sen's slopes, with areas of significant trends overlaid with black hash marks.

area, and mapping errors in fire perimeters may have caused some days where no or minimal reburning occurred to be classified as reburns (false positives) or the reverse (false negatives). The NBAC fire perimeters used for fire spread interpolation are high-quality maps derived from satellite imagery, substantially limiting the likelihood of this error. Of the 9045 short-interval spread days analysed, 89% were larger than 3 ha.

Reburns are relatively uncommon, and long-interval fire spread occurred under a broader range of weather conditions due to the inherently higher likelihood of these events. Together, our minimum mapping unit and possible biases due to the smaller sample size for reburns may partially explain why differences between weather during short- and long-interval spread events were fairly small. We also selected a universal 20-year threshold to identify

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short-interval reburns; however, ecozones have differences in climate and site productivity creating different rates and volumes of fuel accumulation after fire. In future work, ecozone-specific thresholds for the period of time between fires, which are considered short intervals, could be employed. We examined the time series of only the two generally best-performing fire weather variables as determined by the pseudo-R^2; however, the FFMC was not the best predictor of short-interval fire spread in the Boreal Cordillera, which was better represented by DMC or BUI. Despite this limitation, the FFMC and RH models are significant in all ecozones. Reanalysis weather products such as those employed here are often biased low, suggesting that the threshold values for reburning day weather reported here may be conservative, when compared to weather station data.

The SCANFI pre-fire data used here is derived from models predicting forest structure from inventory data. Models of aboveground biomass and canopy closure performed well ($R^2 \geq .76$), but the discrimination between conifer and broadleaf was less confident ($R^2 = .7$), and mixedwood forests were not well represented due to spectral mixing (Guindon et al., 2024). We were unable to incorporate measures of surface fuels into our analyses given that they are difficult to accurately measure over broad extents with multispectral remote sensing. This said, the significance of BUI, which is associated with deep burning in soil organic matter (Wotton, 2009), suggests that non-canopy fuel elements, such as surface fuel continuity or heavy surface fuel loads from coarse woody debris may be important to the likelihood of fire spread, especially within recently burned areas (e.g. Agne et al., 2023) under drought conditions.

Additionally, the CFSDS includes fires that underwent extensive fire suppression, and we cannot discriminate these management interventions across the broad extent of Canada's boreal forest with the available data. Such interventions likely altered fire spread, both by stopping spread when it may have continued without suppression, and by increasing or redirecting spread when using ignitions as a fire management tool.

5 | CONCLUSION

Although the lower flammability of fuels in recently burned areas will offset some of the effects of climate change on fire regimes, both palaeoecological evidence (Carcaillet et al., 2001; Hoecker & Higuera, 2019) and modelling studies (Hart et al., 2019; Hurteau et al., 2019) suggest that climate change can drive increases in fire activity, with fuel limitation of fire spread tempering but not preventing such increases (Abatzoglou et al., 2021). The occurrence of reburning weather days has increased over as much as a quarter of the western boreal forest and is likely to continue to do so (Quilcaille et al., 2023). Society relies on burned areas to reduce fire risk, with natural and prescribed fires and fuel treatments all used as barriers to fire spread (Parisien et al., 2020; Urza et al., 2023). In the future, communities that are currently protected by recently burned areas may be increasingly at risk from fire, as we experience a higher number of days with extreme conditions conducive to short-interval fire spread. The reburning day weather conditions, and the relative probabilities of short- and long-interval fire spread documented here can be used to anticipate future risk to ecosystems from short-interval reburning, and to parameterize models of future fire spread with an accurate representation of the level of constraint in recently burned areas. Communities and fire managers may use this research to anticipate these conditions and prepare for them by developing emergency response plans, and maintaining fuel treatments as they age and fuel reaccumulates. Our results offer insight into the limits of age-limitation of fire spread, and highlight the risk that climate change presents to both ecosystems and societies as extreme fire weather that overwhelms these constraints becomes increasingly common.

Although we show that the odds of fire spread are approximately 50% lower in recently burned areas, this seems to offer only a moderate barrier, which is overwhelmed by only a modest increase the severity of fire weather. This has concerning implications for future ecosystem dynamics in boreal forests. Shortening fire-free intervals are a key mechanism by which the historic carbon sink of boreal forests will become a net source, with younger forests having less time to store carbon in live biomass and organic soils before reburning (Dieleman et al., 2020; Stinson et al., 2011). Climate change-driven increases in short-interval reburning are likely to lead to ecosystem reorganization through direct and indirect effects on vegetation assemblies (Sharma et al., 2022; Stralberg et al., 2018; Weiss et al., 2023). In any disturbance-prone system, a substantial weakening of the negative feedback between disturbance and its bottom-up environmental constraints will invariably lead to ecological consequences (Tepley et al., 2018). In boreal forests of North America, these consequences are becoming increasingly evident, leading to changes in tree-species dominance, loss of old-growth forests (i.e. fire refugia), and even vegetation-type conversions that may persist for decades to centuries. As these phenomena affect a relatively small area of the Canadian landscape at present, anticipating their future likelihood enables land managers to mitigate their negative impacts and retain critical ecosystem services.

AUTHOR CONTRIBUTIONS

Ellen Whitman: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Quinn E. Barber:** Data curation; methodology; writing – review and editing. **Piyush Jain:** Conceptualization; data curation; methodology; writing – review and editing. **Sean A. Parks:** Conceptualization; methodology; writing – review and editing. **Luc Guindon:** Data curation; writing – review and editing. **Dan K. Thompson:** Conceptualization; methodology; writing – review and editing. **Marc-André Parisien:** Conceptualization; data curation; methodology; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest present.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in OSF at https://doi.org/10.17605/OSF.IO/CHD7E. These data were derived from the following resources available in the public domain: Fire perimeter maps from Natural Resources Canada in the National Burned Area Composite (NBAC), and the Canadian National Fire Database (NFDB). These datasets and contact information are available at https://cwfis.cfs.nrcan.gc.ca/. Daily fire spread and weather data from the Canadian Fire Spread Dataset (CFSDS) available in OSF at https://doi.org/10.17605/OSF.IO/F48RY. ERA5-Land data used for time series analysis in this study are available from the Copernicus Climate data store at https://doi.org/10.24381/cds.e2161bac.

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