Global Ecology and Biogeography

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Global Ecology and Biogeography A Journal of Macroecology

RESEARCH ARTICLE OPEN ACCESS

Fighting Fire With Fires: The Fire-Fuel Feedback Effect in Canadian Forests

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Received: 2 July 2025 | **Revised:** 30 November 2025 | **Accepted:** 3 December 2025

Handling Editor: Rachael Helene Nolan

Keywords: 2023 fire season | Canadian forests | climate change | fire activity | fire weather | fire-fuel feedback | spread day

ABSTRACT

Aim: Climate-driven fire increases could be modified by fire-fuel feedback, as recent fires reduce burnable fuels for future fires. Knowing the effects of fire-fuel feedback is essential for more accurate projection of fire activity, which, however, has often been overlooked due to the challenge in its quantification. This study aims to project future fire activity under the changing climates with consideration for fire-fuel feedback effects across Canada.
Location: Canadian forests.
Time Period: 1981–2100.
Major Taxa Studied: Trees.
Methods: We projected future changes in a full set of fire activity variables, including annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS), based on extreme fire weather in Canada. We then incorporated fire-fuel feedback into the projections to quantify its effects in Canadian forests and consequently answered the question of whether the unprecedented 2023 fire season would become a common occurrence in the future.
Results: The feedback from fires within 6–11 years prior showed the strongest power in rectifying fire activity projections, and the feedback effects strengthened as climate change became more severe. By century's end (2080s), under the extreme climate change scenario (RCP8.5), fire-fuel feedback could reduce weather-based AAB, ANF and MFS projections by 21%, 21% and 16%, respectively. Spatially, eastern and northwestern regions may see the greatest fire activity increases, while the strongest feedback effects appear in the south and northwest. In the 2080s, under RCP8.5, years with more extensive fires than 2023 may occur once every 9 years in regions most affected by the unprecedented 2023 fire season.
Main Conclusions: The results indicate that fire-fuel feedback could modestly mitigate climate-driven increases in future fire activity in Canadian forests. With more accurate projections that account for such feedback effects, the extraordinary 2023 fire season could be considered a low-frequency but more plausible occurrence in the future.

[Corrections added on 30 January 2026, after first online publication: the author, Wanli Wu's affiliation has been updated in this version.]

Weiwei Wang and Xianli Wang contributed equally to this study.

1 | Introduction

As global climate change continues, Canada is facing extended fire seasons with more uncontrollable wildfires and growing burned areas (Curasi et al. 2024; Flannigan et al. 2013; Wang et al. 2022). The record-breaking 2023 fire season (Kirchmeier-Young et al. 2024; Jain et al. 2024; Jones et al. 2024), with about 15 million hectares burned, escalated concerns about future challenges even further (Boulanger et al. 2014, 2018; Flannigan et al. 2005). Wildland fire activity is affected by a wide range of biophysical and anthropogenic factors including vegetation features, topographic variations, ignition patterns, weather conditions and human activities (Bowman et al. 2009, 2020; Jones et al. 2022; Kelley et al. 2019; Scholten et al. 2024). Among these, weather and climate variations are arguably the dominant drivers of the patterns and variability in fire activity at large spatial and temporal scales (Abatzoglou et al. 2018; Abatzoglou and Kolden 2013; Bedia et al. 2015; Margolis et al. 2025). In addition to their direct influences (e.g., ignition and spread), weather and climate can indirectly modify fire activity by altering fuel dryness through ambient humidity and by modulating fuel types through growing environment conditioning (Abatzoglou and Williams 2016; Krawchuk and Moritz 2011; Stevens-Rumann et al. 2018). However, direct changes in fuel distribution and availability may override the impacts of weather and climate and therefore reshape fire activity (Pausas and Paula 2012; Pausas and Ribeiro 2013). Although sustained efforts have been made to project fire activity (i.e., the extent and frequency of fires) changes into the future (Boulanger et al. 2014, 2018; Flannigan et al. 2005; Wang et al. 2022), the effect of direct changes in fuel has rarely been considered in these efforts.

In Canada, the size of any large fire has been found to be determined by the number of 'spread days' – days with certain fire weather conditions that lead to substantial fire growth (Podur and Wotton 2011; Wang et al. 2014). The number of realised spread days (NSD) has shown to be a powerful predictor of key fire activity variables (Wang et al. 2021, 2022), including annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS). Defined solely by fire weather, potential spread days (PSD) refer to fire-conducive weather conditions that are more prone to non-negligible fire spread. The Canadian Forest Fire Weather Index System (CFWIS; Lawson and Armitage 2008; Van Wagner 1987) has been developed to measure potential fuel moisture and assess fire danger based only on weather observations. The CFWIS components have been used as successful indicators to identify potential spread days (Podur and Wotton 2011; Wang et al. 2023). The connections between weather-inferred PSD and on-the-ground realised spread days (Wang et al. 2014) make it possible to project changes in fire activity based on weather projections (Wang et al. 2022). Model projections demonstrate the broad consensus of evident increases in future fire extent and frequency driven by warming climates across Canada (Boulanger et al. 2014, 2018; Curasi et al. 2024; Flannigan et al. 2005; Wang et al. 2022).

Fuel characteristics, including fuel availability (amount and aridity), type and continuity, are some of the most foundational factors shown to be able to mediate or override the effect of changing climate on fires (Hurteau et al. 2019; Krawchuk and Moritz 2011; Pausas and Paula 2012; Pausas and Ribeiro 2013; Price et al. 2015). In particular, fuel limitations caused by antecedent fires may initiate fire-fuel feedback to constrain subsequent fire events. This may provide a nature-based mechanism to alleviate climate-driven increases in future wildfires. For example, in Canada, recently burned boreal forests were found to resist burning for around 30 years due to fuel limitations, unless extreme fire-conducive weather conditions enable reburning (Parks et al. 2018; Whitman et al. 2019, 2024). In addition, the combination of high burn severity and increasing drought stress following fires may hinder post-fire ecosystem recovery and lead to regeneration failure, such as those found in the mountain and boreal forests in North America (Davis et al. 2019; Littlefield et al. 2020; White et al. 2023). Consequently, fuels may be reduced for subsequent fires. These fire-fuel feedback effects may mitigate the potentially amplified climate-based estimates of future fire activity (Abatzoglou et al. 2021; Hurteau et al. 2019).

Canada's vast and diverse ecosystems, spanning from the Atlantic to the Pacific and into the Arctic, sustain distinct fire activity patterns (Ecological Stratification Working Group (ESWG) 1996; Hanes et al. 2019; Stocks et al. 2002). Understanding the roles of climate and fire-fuel feedback on fire activity is essential for managing wildfire impacts and preserving environmental integrity and resilience (Flannigan et al. 2006, 2009). Knowing the effects of fire-fuel feedback may also allow more accurate quantification of fuel treatment effectiveness (Price et al. 2015), which could help wildfire risk reduction efforts, especially for communities in the forested area. Although fire-fuel feedback has been known to affect the accuracy of future fire activity projections (Boulanger et al. 2017; Krawchuk and Cumming 2011; Marchal et al. 2020), a national-scale quantification of how fuel reduction from previous fires influences future fire extent and frequency is still lacking. More realistic projections of future fire activity by considering such fire-fuel feedback may enable us to more accurately address the critical question prompted by the unprecedented fire year of 2023: Will Canada's extreme 2023 fire season become common by the end of the century?

Building on the known relationships between spread days and fire activity (Wang et al. 2021, 2022), this study aims to (i) project future changes in a full set of fire activity variables (AAB, ANF and MFS) under the changing climates with different scenarios in Canada, (ii) incorporate the feedback of fire-induced fuel limitations into the projections and quantify the effect of fire-fuel feedback on constraining future fire activity and (iii) estimate the frequency and likelihood of future fire years that are more severe than the 2023 fire season in Canadian forests.

2 | Methods

2.1 | Study Area

Canada has a holistic, hierarchical ecological stratification framework that was established to delineate and classify its land surface according to the ecological distinctiveness resulting from the interplay of diverse abiotic and biotic factors (Ecological Stratification Working Group (ESWG) 1996). This framework consists of four levels of generalisation: ecozones, eco-provinces, ecoregions and eco-districts. We used the Canadian ecozone as the analysis unit, a sub-continental scale at which numerous fire-related studies have been conducted. Such studies include estimating various aspects of fire activity such as burned areas, number of fires and burn severity (Guindon et al. 2021; Hanes et al. 2019), post-fire vegetation recovery patterns (White et al. 2022, 2023), greenhouse gas emissions from fires (Amiro et al. 2001, 2009) and connections between fire activities and meteorological (weather and climate) conditions (Flannigan et al. 2005; Wang et al. 2022).

In this study, 10 Canadian ecozones with abundant forest fires were used for the analyses (Figure 1A). These ecozones cover the primary forested landmass of Canada, featuring three dominant biomes: the boreal forests that extend across central Canada and to the southern edge of the tundra, the mountain and subalpine forests in the Rocky Mountains of western Canada and the temperate broadleaf and mixed forests on the east coast and in the Great Lakes area. The ecozones include Taiga Plains (TP), Boreal Plains (BP), Taiga Cordillera (TC), Boreal Cordillera (BC), Montane Cordillera (MC), Hudson Plains (HP), Taiga Shield (TS) and Boreal Shield (BS). Taiga Shield and Boreal Shield ecozones were subdivided into west and east components (TSW and TSE; BSW and BSE) due to their distinctions in climate characteristics and fire activity (Stocks et al. 2002). Most of the study area is relatively flat, with the exception of the western Cordillera region, which is characterised by diverse mountain ranges including the Rocky Mountains and a plateau region.

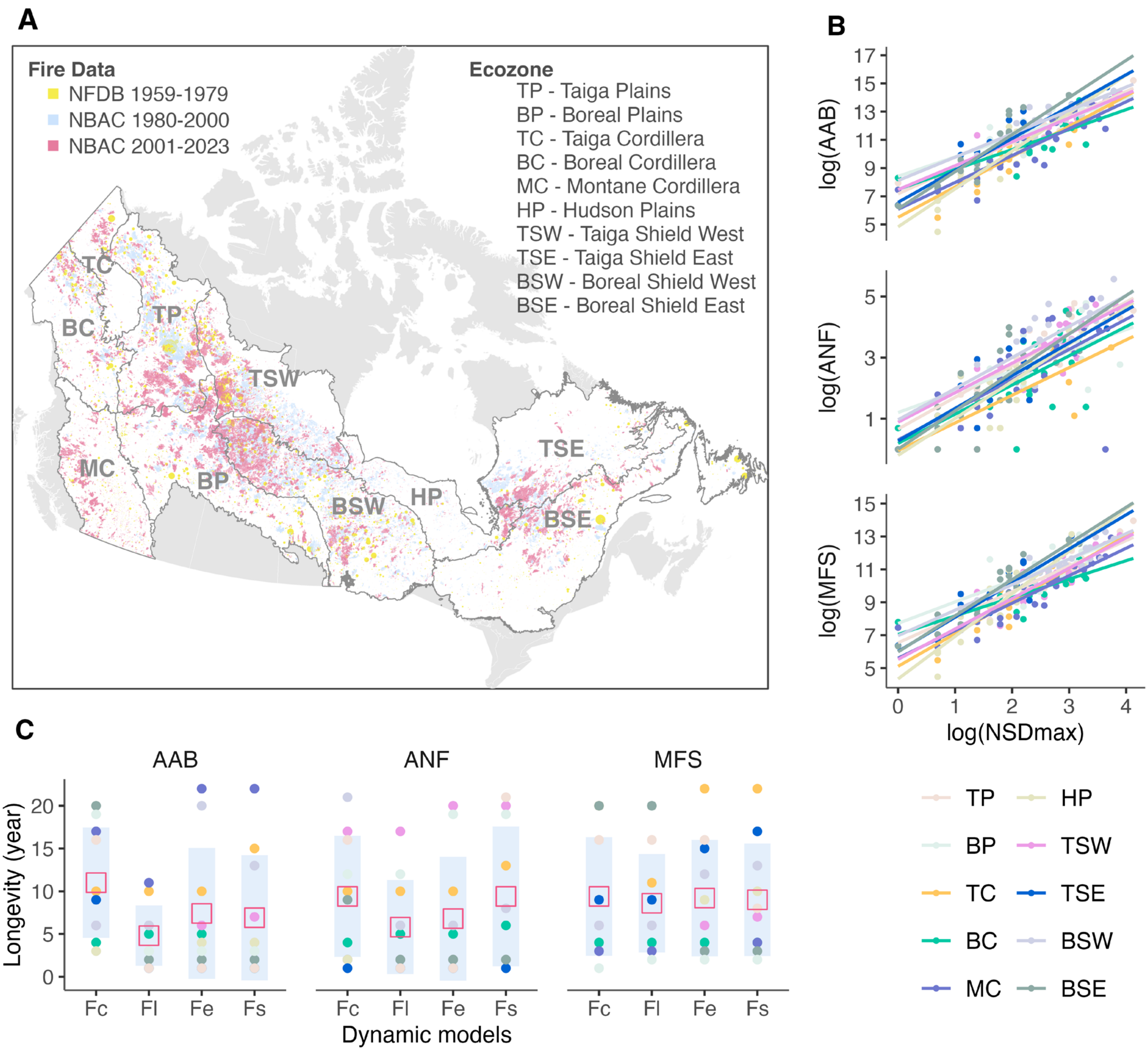

FIGURE 1 | Fire history and fire activity model summary in the Canadian ecozones. (A) Study area and historical fire data. NFDB and NBAC refer to the National Fire Database fire point data and the National Burned Area Composite dataset, respectively. (B) Static models by ecozone. (C) Fire-fuel feedback longevities in the dynamic models. Red square and light blue shading represent mean and standard deviation. Map lines delineate study areas and do not necessarily depict accepted national boundaries. Fire activity variables: AAB, annual area burned; ANF, annual number of fires; MFS, annual maximum fire size.

2.2 | Data and Data Management

2.2.1 | Fire Data

The National Burned Area Composite (NBAC) dataset (Hall et al. 2020), the most consistent and accurate national fire polygon database in Canada (Skakun et al. 2022), was used to derive fire activity variables from 2001 to 2023 (Figure 1A); these include annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS) for the ecozones. Only fires with a burned area ≥ 50 ha were included in the analyses (Wang et al. 2021, 2022). To calculate the feedback term in the dynamic models, the NBAC data from 1980 to 2000 and the National Fire Database (NFDB) fire point data (Stocks et al. 2002) from 1959 to 1979 (Figure 1A) were used to generate the longest, reliable record of observed AAB (Hanes et al. 2019), ensuring consistency and minimising data uncertainties within the modelling framework centered on the periods after 1980 (see Section 2.3: Analysis).

2.2.2 | Fire Weather Data

Following Wang et al. (2017, 2022), we randomly sampled 524 points that were at least 60 km apart from an interpolated 3-km daily fire weather product to calculate the CFWIS (Lawson and Armitage 2008; Van Wagner 1987) components. Two CFWIS variables, Fire Weather Index (FWI) and Duff Moisture Code (DMC), were used to determine PSD distributions for the ecozones, which were in turn used to project NSD distributions and therefore fire activity changes. We considered projected fire activity changes across four periods: the baseline (1981–2010) and three future periods including the 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100). Future projections used the daily fire weather data of three general circulation models (GCMs: CanESM2, CSIROMk3-6-0 and HadGEM2-ES) for three representative concentration pathway (RCP) climate change scenarios (RCP2.6, RCP4.5 and RCP8.5) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). The three GCMs were chosen through a best-performance selection procedure that evaluated model skill scores based on probability density functions (PDFs), identifying the GCMs that best captured maximum temperature, minimum temperature and precipitation patterns across Canadian ecozones (Perkins et al. 2007; Wang et al. 2017, 2022).

2.2.3 | Generating Realised Spread Days (NSD)

Daily fire growth data from 2001 to 2023 were used to derive NSD. The fire growth data were produced using the NBAC fire perimeters (≥ 50 ha) in accordance with fire hotspots from the Moderate Resolution Imaging Spectroradiometer (MODIS, 1-km resolution) during 2001–2023 and from the Visible Infrared Imaging Radiometer Suite (VIIRS, 375-m resolution) during 2013–2023, based on data availability. Daily growth of each fire event was mapped at a 30-m resolution following the methods described by Parks (2014), which spatially interpolate the day of burning from MODIS and VIIRS hotspots within the NBAC fire perimeters (Wang et al. 2014, 2017). In total, 6210 fire events were included, ranging from 185 to 1434 events per ecozone. A realised spread day was identified by a rate of spread threshold of 1 m min^{-1}, assuming a 4-h burning period per day and a circular fire growth model (Hirsch 1996; Wang et al. 2014). NSD for each fire from 2001 to 2023 was counted, and the annual maximum NSD (NSD_{max}) was generated across all fire events in that year for each ecozone.

2.2.4 | Generating Potential Spread Days (PSD)

PSD correspond to extreme weather conditions that are more likely to produce considerable fire spread (Podur and Wotton 2011; Wang et al. 2014) and were defined as days when FWI ≥ 19 (Podur and Wotton 2011) in this study. The fire weather data from 2001 to 2023 were used to generate PSD distributions for the development of the link functions between PSD and NSD. We combined the last 10 years of the baseline period (2001–2010) and the first 13 years of the 2020s (2011–2023), which resulted in nine modelled data sets (3 GCMs × 3 RCPs for the 2020s) for each ecozone. A Monte Carlo simulation was performed to randomly 'ignite' and 'extinguish' 50,000 hypothetical fires during any consecutive period of DMC > 20 (i.e., the potential burning period) for each ecozone (Wang et al. 2014, 2017). Effective PSD were counted as those days with FWI ≥ 19 between the simulated ignition and extinguishment dates for each iteration. To prepare the inputs for fire activity projections, we obtained the annual maximum PSD (PSD_{max}) from the fire weather data by period, GCM and RCP scenario. PSD_{max} was calculated as the max number of PSD (FWI ≥ 19) within a consecutive period when DMC > 20 (Podur and Wotton 2011; Wang et al. 2014) across all points within each ecozone for that year.

2.3 | Analysis

We built the AAB, ANF and MFS prediction models without and with fire-fuel feedback, referred to as the static and dynamic models. Models were built by ecozone using observed fire and weather data for the period of 2001–2023 (Figure S1). Static models were based solely on NSD_{max}, whereas dynamic models incorporated one of four different feedback terms to capture fuel constraints resulting from previous fires. To project fire activity changes over time, the link functions between PSD and NSD were developed and applied to project NSD_{max} distributions based on the distributions of PSD_{max} (derived from the fire weather data). The converted NSD_{max} distributions were used as the inputs for static and dynamic models to project AAB, ANF and MFS distributions for the four periods under different GCMs and RCP scenarios. The relative differences in fire activity projections between static and dynamic models were calculated to quantify the effect of fire-fuel feedback that was featured in the dynamic models. At the end, the projections of AAB, ANF and MFS were compared with those from the 2023 fire season to evaluate how current benchmarking of extreme fire activity aligns with anticipated changes in the future.

2.3.1 | Building Static and Dynamic Models of Fire Activity Variables

Static models of AAB, ANF and MFS (variable y in Equations 1 and 2) were built based on NSD_{max} by ecozone following Wang et al. (2022):

$$\log(y) = \alpha_s + \beta_s \times \log(\text{NSD}_{\max}). \quad (1)$$

We updated the functions in Wang et al. (2022) using extended daily fire growth data from 2001 to 2023, which generated similar and consistent outputs with Wang et al. (2022). The dynamic models were developed by incorporating a fire-fuel feedback term F that account for fuel constraints caused by recent burning:

$$\log(y) = \alpha_d + \beta_{d1} \times log(\text{NSD}_{\max}) + \beta_{d2} \times \log(F). \quad (2)$$

The feedback term F was calculated based on AAB from previous years, as the reduced availability of burnable fuels measured by previous AAB theoretically limits both the extent and frequency of subsequent fires. Four forms of F were considered to effectively capture fire-fuel feedback effects:

$$F_c = \sum_{i=1}^{\tau} \text{AAB}_i, \quad (3)$$

$$F_l = \sum_{i=1}^{\tau} \text{AAB}_i / i, \quad (4)$$

$$F_e = \sum_{i=1}^{\tau} \text{AAB}_i \times e^{-(i-1)\times e/\tau}, \quad (5)$$

$$F_s = \sum_{i=1}^{\tau} AAB_i \times \left(1 + \cos\frac{\pi \times i}{\tau + 1}\right) / 2. \quad (6)$$

Here, F_c represents a constant form that assigns the same weight to all previous years, whereas F_l, F_e and F_s represent fading forms with linearly, exponentially and sinusoidally (Abatzoglou et al. 2021) decreasing weights, respectively, for older pre-fire years. τ is the longevity of the feedback term and was tested with values ranging from 1 year to 22 years. For example, values for modelling the year 2001 would correspond to a pre-fire period ranging from 2000 (1 year) to 1979–2000 (22 years). The upper limit of 22 years was determined by the longest available pre-fire period for 1981, the start of the baseline, given the historical fire observations extend back to 1959. The final choice of τ was guided by ecological rationale, i.e., only models with a negative coefficient for the feedback term were retained as candidates as we assume the considered feedback should impose constraint effects on fire activity, and model performance, i.e., models with higher accuracy (adjusted R^2) were selected. If no longevity values yielded a model with a negative feedback coefficient, such as F_l and F_e forms of ANF models for the TP ecozone, models with a near-zero feedback coefficient, representing a very weak feedback effect, were selected.

Model performance was evaluated using the adjusted fitting R^2 for the model development period from 2001 to 2023 and validated using the PDF-based skill score (S_{score}; Perkins et al. 2007) for the baseline period from 1981 to 2010. The S_{score} measures the common area between the PDFs of modelled and observed values, with a score close to one indicating higher agreement between the two distributions:

$$S_{\text{score}} = \sum_{i=1}^{n} \text{minimum}(Z_{m,i}, Z_{o,i}), \quad (7)$$

where n is the number of bins used to calculate the PDFs, $Z_{m,i}$ is the frequency of modelled values in bin i, and $Z_{o,i}$ is the frequency of observed values in bin i.

2.3.2 | Projecting $\text{NSD}_{\max}$ Distributions Based on PSD-NSD Linkage

To generate $\text{NSD}_{\max}$ distributions over time, we created the link function between PSD and NSD for each ecozone. On the basis of the simulated PSD distributions for the period of 2001–2023, we fitted a linear regression model for the standardised, log-transformed frequency of each PSD distribution. This resulted in nine models given the nine modelled data sets for each ecozone. The coefficients for the nine models of PSD frequency were averaged. Similarly, a linear regression model was fitted for the standardised, log-transformed frequency of the NSD distribution from 2001 to 2023 by ecozone. The conversion functions between PSD and NSD were created by equating the two linear regression models (Wang et al. 2014). Using the link functions between PSD and NSD, $\text{NSD}_{\max}$ distributions were projected by period, GCM and RCP scenario based on the respective $\text{PSD}_{\max}$ distributions accordingly.

2.3.3 | Projecting Future Fire Activity and Quantifying Fire-Fuel Feedback Effects

Based on the estimated $\text{NSD}_{\max}$, AAB, ANF and MFS were projected using static models for each period, GCM and RCP scenario. Dynamic models were applied to the full modelling period, from 1981 to 2100, using the feedback term calculated from observed AAB prior to 1981 and from model-derived AAB thereafter under different feedback forms, GCMs and RCP scenarios. Shifts of fire activity were calculated as the ratio of median AAB, ANF and MFS changes between future periods and the baseline. The effect of fire-fuel feedback was quantified as the percentage reduction (%) of the median AAB, ANF and MFS projected by the dynamic models relative to that of the static models. To present an overall overview across the country, we calculated the weighted average of AAB, ANF and MFS shifts and feedback effects for all ecozones, where the weights were derived from median observed AAB, ANF and MFS during the baseline period (1981–2010) for each ecozone (Wang et al. 2022).

2.3.4 | Comparing Future Projections With the 2023 Fire Season

Canada's unprecedented 2023 fire season (Kirchmeier-Young et al. 2024; Jain et al. 2024; Jones et al. 2024) prompted a critical question about the frequency and likelihood of similarly extreme or more severe fire years in the future. To suggest an answer to this question, we compared fire activity projections with observations from the 2023 fire season and calculated the percentage of years (maximum of 30 years per period) in which projected AAB, ANF, or MFS exceeded the levels of the 2023 fire season. The comparison was conducted among different models (static or dynamic models), periods, GCMs and RCP scenarios in each ecozone, with a focus on ecozones that experienced unprecedented area burned in 2023.

3 | Results

3.1 | Feedback From Fires Within 6–11 Years Prior Optimises Fire Activity Modelling

The link functions used to convert the number of weather-based potential spread days (PSD) to observed realised spread days (NSD) exhibited strong performance by Canadian ecozone. The functions averaged adjusted R^2 (R^2_{adj}) of 0.91 (±0.07) and 0.77 (±0.10) for all linear regression models for PSD and NSD, respectively (Table S1). The static fire activity prediction models based on NSD_{max} (Figure 1B) showed averaged R^2_{adj} of 0.76 (±0.12), 0.50 (±0.18) and 0.76 (±0.13) for modelling annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS), respectively, across the 10 ecozones (Table S2). In comparison, the dynamic models with fire-fuel feedback achieved higher R^2_{adj} of 0.78 (±0.09) and 0.54 (±0.16) for modelling AAB and ANF, respectively, and a similar R^2_{adj} of 0.76 (±0.12) for modelling MFS. The constant form of fire-fuel feedback (averaged R^2_{adj} of 0.79 for AAB, 0.57 for ANF and 0.77 for MFS) slightly outperformed the fading forms (averaged R^2_{adj} of 0.77 for AAB, 0.53 for ANF and 0.76 for MFS). Model validation for the baseline period from 1981 to 2010 showed strong agreement between modelled and observed distributions of AAB, ANF and MFS, with an averaged skill score (S_{score}) of 0.78 (±0.11) using the static and dynamic models (Figure S2 and Table S2).

The performance of dynamic models fluctuated with feedback longevity values (Figures S3–S5). The averaged optimal longevities were 8 (±7) years for modelling AAB and ANF and 9 (±6) years for modelling MFS over all feedback forms across the ecozones (Figure 1C). The choice of longevity also varied with feedback forms, with the optimal longevities averaging 10 (±7) years for F_c, 6 (±5) years for F_l and 8 (±7) years for F_e and F_s over the three fire activity variables. In general, dynamic models for Taiga Cordillera (TC), Taiga Shield West (TSW), Boreal Shield West (BSW) and Taiga Plains (TP) selected a greater longevity of 11 (±6) years on average for modelling fire activities, while the averaged longevity was 6 (±6) years for the other ecozones.

3.2 | Fire-Fuel Feedback Enhances With More Severe Climate Changes

By the end of this century, static models projected averaged 4.39-, 1.88- and 4.12-fold increases of AAB, ANF and MFS, respectively, over all GCMs and RCP scenarios across the country (Figure 2 and Tables S3–S5). These shifts were reduced to 3.16-, 1.45- and 2.80-fold by dynamic models, which are 21%, 21% and 16% reductions in comparison. In general, the fading forms were more conservative than the constant form, with mean shift ratios of 3.24 and 2.91 for AAB, 1.55 and 1.15 for ANF and 2.96 and 2.32 for MFS in the 2080s, respectively. Overall, the effect of fire-fuel feedback strengthened as the time period progressed (Figure 2 and Tables S3–S5), and the feedback constrained fire activity increases by averaged 11% (11% for AAB and ANF; 10% for MFS) in the 2020s, 14% (15% for AAB; 16% for ANF; 12% for MFS) in the 2050s and 19% (21% for AAB and ANF; 16% for MFS) in the 2080s across the ecozones. The fire-fuel feedback considered was also more profound under severe climate change scenarios, with averaged reductions of 12% (13% for AAB; 12% for ANF; 10% for MFS) under RCP2.6, 13% (14% for AAB; 15% for ANF; 11% for MFS) under RCP4.5 and 19% (21% for AAB and ANF; 16% for MFS) under RCP8.5 over all periods and GCMs.

Spatially, eastern (Hudson Plains [HP], Taiga Shield East [TSE] and Boreal Shield East [BSE]) and northwestern (TC) ecozones showed the greatest increases in all fire activity variables by the end of this century, particularly under RCP8.5 (Figure 3 and Tables S6–S8; see Figures S6, S7 for RCP2.6 and RCP4.5). In these ecozones, dynamic models projected mean shift ratios of 8.29 (static models: 12.86), 1.90 (2.63) and 5.59 (10.37) for AAB, ANF and MFS, respectively, in the 2080s over all GCMs and RCP scenarios. The remaining ecozones showed mean shift ratios of 2.14 (static models: 2.64) for AAB, 1.31 (1.64) for ANF and 2.09 (2.38) for MFS during the same period. The fire-fuel feedback demonstrated the strongest constraint effects in the southern and northwestern ecozones, particularly in TC (reducing increases in AAB, ANF and MFS by an average of 43%, 52% and 40% in the 2080s over all GCMs and RCP scenarios) and BSE (reducing them by 28%, 30% and 26%). Considerable feedback effects were also found for specific fire activity variables in some other ecozones, mainly in the south, such as in BSW (30%) and Boreal Plains (BP) (25%) for AAB, in Montane Cordillera (MC) (31%) and BP (24%) for ANF and in TSE (23%) and BSW (21%) for MFS.

3.3 | Years as Extreme as 2023 Are Expected to Be More Common by the End of This Century

In the extreme fire season of 2023, five ecozones experienced unprecedented fire activity, with area burned exceeding all records observed between 1959 and 2022, including TP, BP, HP, TSE and BSE (Figure S8). As projected fire activity increases over time, the frequency of years surpassing the 2023 fire season escalates across these ecozones, especially under severe climate change scenarios (Figures 4, 5 and Table S9). On the basis of static model projections, years exceeding 2023 in AAB, ANF and MFS were estimated to occur approximately once every 6.6 years (15.1%), 7.8 years (12.9%) and 6.3 years (15.8%), respectively, by the end of this century under RCP8.5 across these ecozones. With consideration for various forms of fire-fuel feedback, these values were reduced to once every 8.8 years (11.4%), 14.7 years (6.8%) and 12.5 years (8.0%) on average (Figures 4, 5 and Table S9; see Figures S9, S10 for RCP2.6 and RCP4.5). Among the five ecozones, TSE and BSE in the east were estimated to experience more years with extensive fire extents comparable to that of 2023 (Figures 4–5; see Tables S10–S12 for the summaries of all ecozones). Summarised across the two eastern ecozones, dynamic models with fire-fuel feedback projected 25.1% (static models: 30.6%) and 19.0% (28.9%) of years in the 2080s with AAB and MFS exceeding the 2023 fire season under RCP8.5.

4 | Discussion

This study investigated the influences of fuel constraints caused by previous fires, i.e., fire-fuel feedback, on

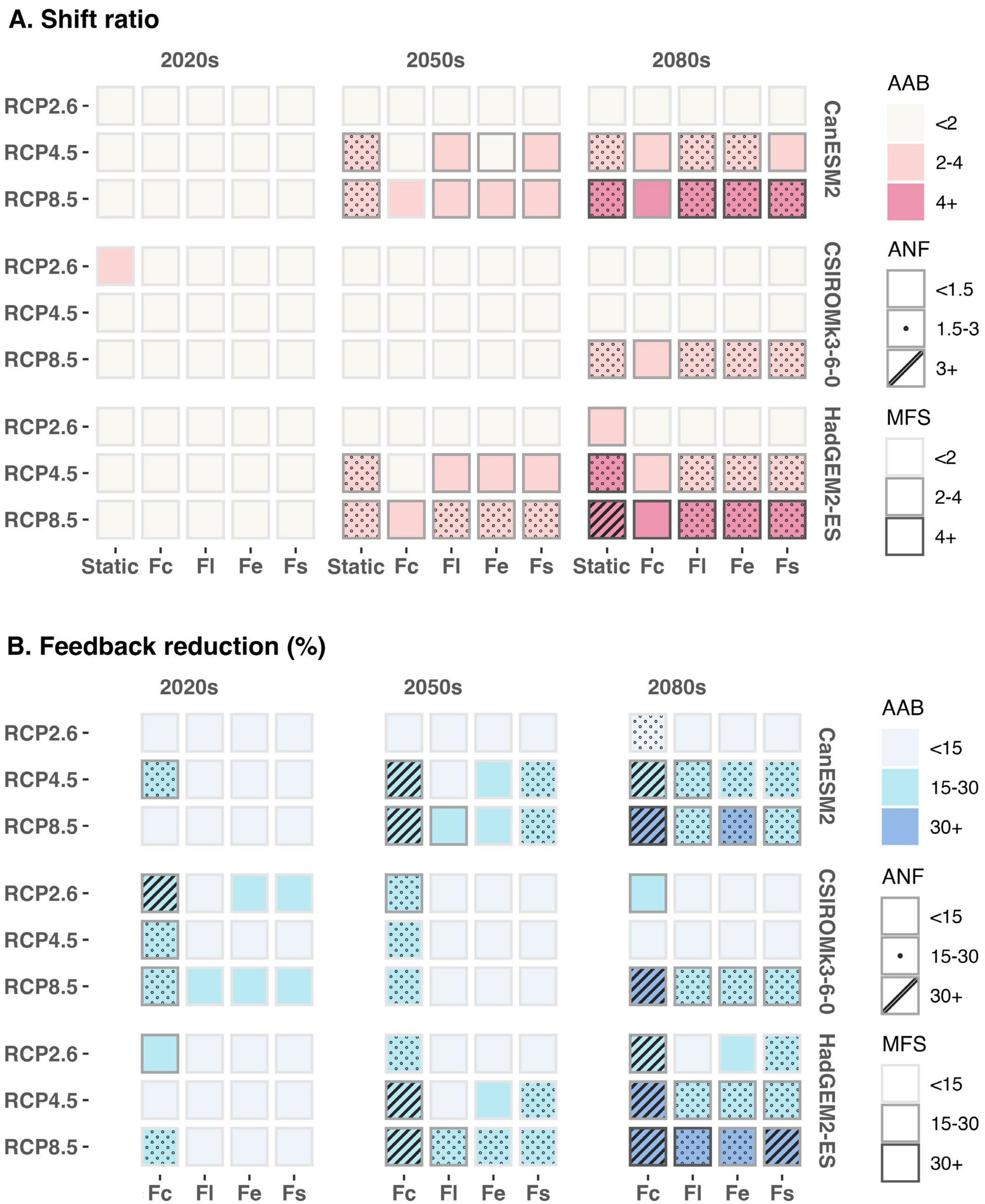

FIGURE 2 | Overall fire activity shifts and fire-fuel feedback effects under changing climates. (A) Shift ratios of annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS) projected by static models and dynamic models with different forms of fire-fuel feedback (F_c, F_l, F_e and F_s; see definitions in Methods) across the country. (B) Percentage reductions (%, i.e., fire-fuel feedback effect size) of AAB, ANF and MFS projected by dynamic models relative to that of the static models. The results showed the weighted average over the 10 ecozones where the weights were calculated by the median observed AAB, ANF and MFS for the baseline period (1981–2010). See Tables S3–S5 for more details.

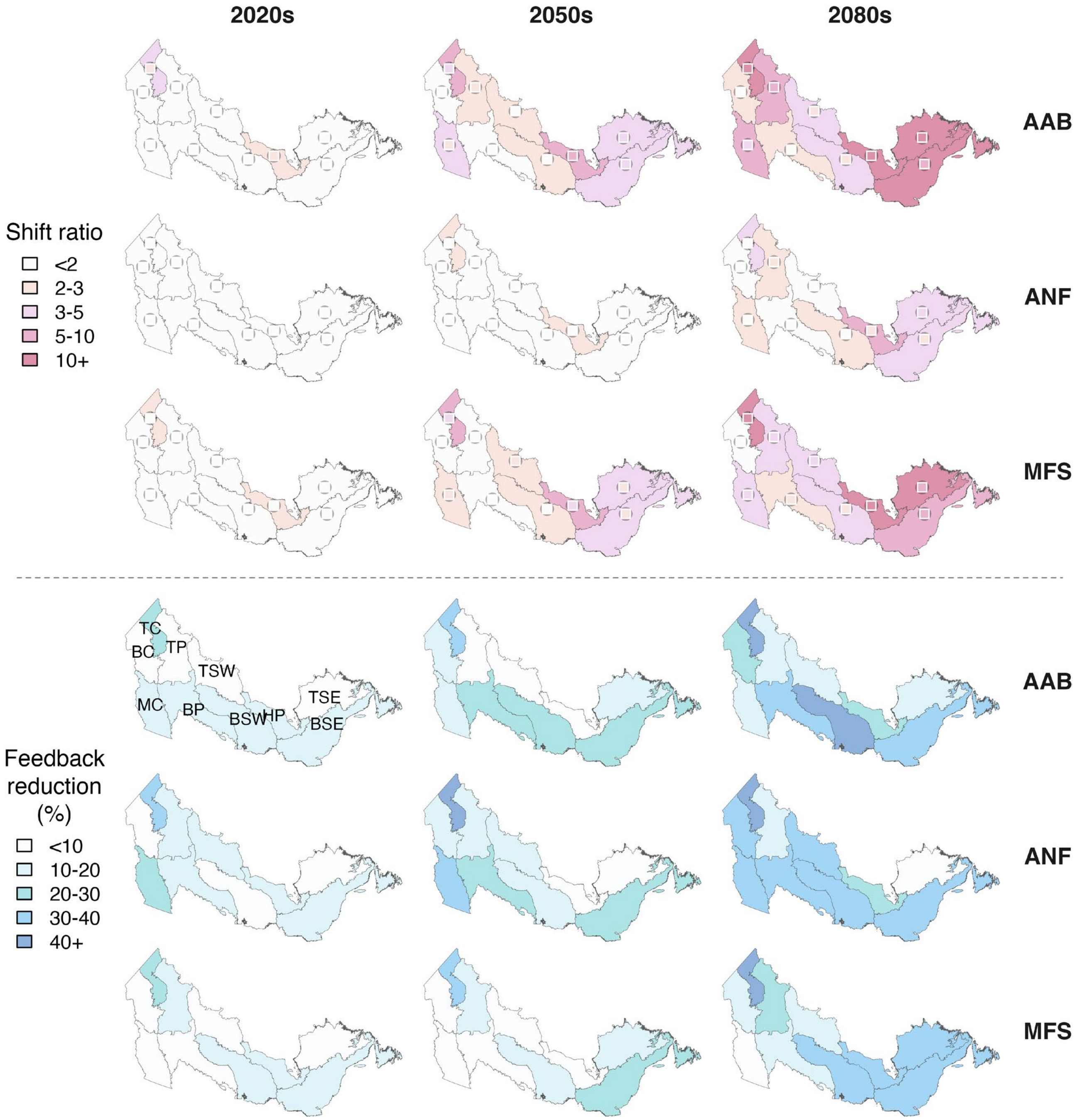

FIGURE 3 | Fire activity shifts and fire-fuel feedback effects under RCP8.5 scenario. The shift ratios (background: Static models; inner square: Dynamic models) and feedback reductions were averaged over three GCMs, and the dynamic model results were averaged over the four forms of fire-fuel feedback (F_c, F_l, F_e and F_s). See Tables S6–S8 for more details and Figures S6, S7 for RCP2.6 and RCP4.5. Fire activity variables: AAB–annual area burned, ANF–annual number of fires, MFS–annual maximum fire size.

climate-driven changes in future fire activity, including annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS), across Canada. We found that dynamic models with the feedback from fires within 6–11 years prior exhibited the strongest power in rectifying weather-based fire activity projections. When accounting for fire-fuel feedback, our results showed approximately threefold increases in AAB (similar to that of the 2024 fire season with about 5.3 million hectares burned; Canadian Interagency Forest Fire Centre (CIFFC) 2024) and MFS and less than twofold increase in ANF by the end of the century summarised over all GCMs and RCP scenarios. Overall, the feedback may mitigate the overestimated future fire activity by 11%–19% over all periods, GCMs and RCP scenarios, with stronger effects identified in later periods and under more severe RCP scenarios, reflecting the increased fuel limitation imposed by greater projected burned areas. Spatially, eastern and northwestern ecozones showed the greatest increases in future fire activity (see also Flannigan et al. 2005; Wang et al. 2022), whereas the strongest fire-fuel feedback effects were found in the southern and northwestern ecozones. On the basis of projections accounting for fire-fuel feedback, by the end of this

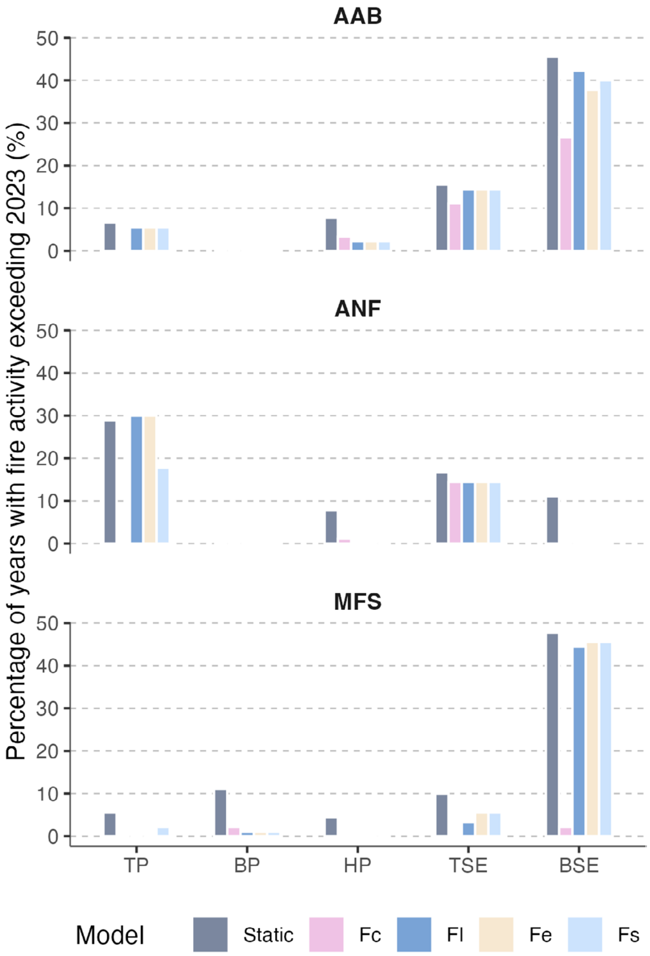

FIGURE 4 | Likelihood of extreme fire seasons in 2080s under RCP8.5 scenario. The percentage of years in which annual area burned (AAB), annual number of fires (ANF), or annual maximum fire size (MFS) was projected to exceed the 2023 fire season was averaged over three GCMs. Only ecozones with unprecedented area burned in 2023 were presented. See Table S10–S12 for more details.

century under RCP8.5, years with more extensive area burned than the 2023 fire season were estimated to occur approximately once every 9 years for the ecozones that experienced unprecedented area burned in 2023. This indicates that the extraordinary 2023 fire season in Canada could still be considered an infrequent occurrence in the years to come.

The dynamic models in this study integrated the negative fire-fuel feedback with the dampened effects of fuel constraints on subsequent fires materialised from historical combustion. The negative feedback contributed to explaining more variances in fire activity, as indicated by the improved modelling accuracy and modestly alleviated projected increases in future fire activity across Canada (see also Abatzoglou et al. 2021). Our results demonstrated the role of fuel constraints in counteracting the promoting effects of warming climates on fires, which also indicates the potential efficacy of intentional fuel management tactics (e.g., mechanical thinning and prescribed burning) in mitigating fires (Fernandes and Botelho 2003; Price et al. 2015). In addition, the feedback effects in our study strengthened over time and as climate change became more severe. Similarly, previous research found that age-related feedback induced by fire and harvesting could significantly reduce projected increases in burn rates, particularly in areas with high projected fire activity and under severe climate forcing, where the projected burn rates could be 50% lower in 2100 with consideration for this feedback (Boulanger et al. 2017). In our study, the strengthening feedback effect stems from the ecological process captured by the dynamic models, where larger precedent fires could result in greater fuel constraints on subsequent fires. This also elucidates the substantial projected fire activity increases and strong feedback effects in some eastern and northwestern ecozones (e.g., BSE and TC). However, considerable feedback effects could also emerge when dynamic models consistently produce low fire activity increases over time, even with mild increases projected by static models (e.g., BSW and BP).

The choice of longevity for feedback terms in the dynamic models was based on model plausibility (non-positive coefficients for the feedback term) and accuracy (adjusted fitting R^2), which may not appropriately reflect the ecological thresholds for post-fire recovery in the ecozones. The selected longevity represents the optimal feedback effectiveness at the ecozone scale, which may not capture the longer fire-resistant periods of 30–50 years observed in some local boreal forests (e.g., Erni et al. 2017; Héon et al. 2014; Johnston et al. 2015; Thompson et al. 2017), particularly given the maximum longevity of 22 years in this study due to data limitations. However, the results did show some consistency with previous studies. For example, the average optimal longevity for the constant form of fire-fuel feedback (10 years) aligns closely with the national mean spectral recovery rate (10.6 years; validated by the direct measures of canopy height and canopy cover derived from airborne laser scanning data) proposed by White et al. (2022). The optimal longevity of 6–8 years for the fading forms falls within the short-term, rapid recovery of 5–10 years following fires in most Canadian forests (Bartels et al. 2016). In Canada, the local recovery trajectory is highly variable and associated with pre-fire forest composition and structure, post-fire weather and site conditions and fire severity (Bartels et al. 2016; White et al. 2023; Whitman et al. 2019, 2024). The polynomial relationship between time since fire and forest structure recovery (Bartels et al. 2016) also confirms the challenges to identify robust, generalised recovery thresholds at the ecozone scale. Our method provides a feasible way to effectively capture fire-fuel feedback effects in the ecozones. More robust thresholds for the longevity could be discovered by including the aforementioned factors that control post-fire vegetation recovery. Embedding these factors into the models is undoubtedly challenging and needs longer series of observation data.

We recognise that the dynamic models are limited by the absence of fire- or climate-induced conversion of vegetation types and changes in forest composition, which may initiate different feedback effects on subsequent fire activities (Abatzoglou et al. 2021; Chaste et al. 2019; Coop et al. 2020). For example, the potential increase of less-flammable deciduous species in boreal forests under a warmer climate may further mitigate projected fire activity (Foster et al. 2022; Girardin et al. 2013; Stralberg et al. 2018; Terrier et al. 2013). However, in Canada, most areas burned by forest fires retain their resilience without experiencing subsequent regeneration failure (Baltzer et al. 2021; Hart et al. 2019; White et al. 2023), which justifies the exclusion of such sophisticated

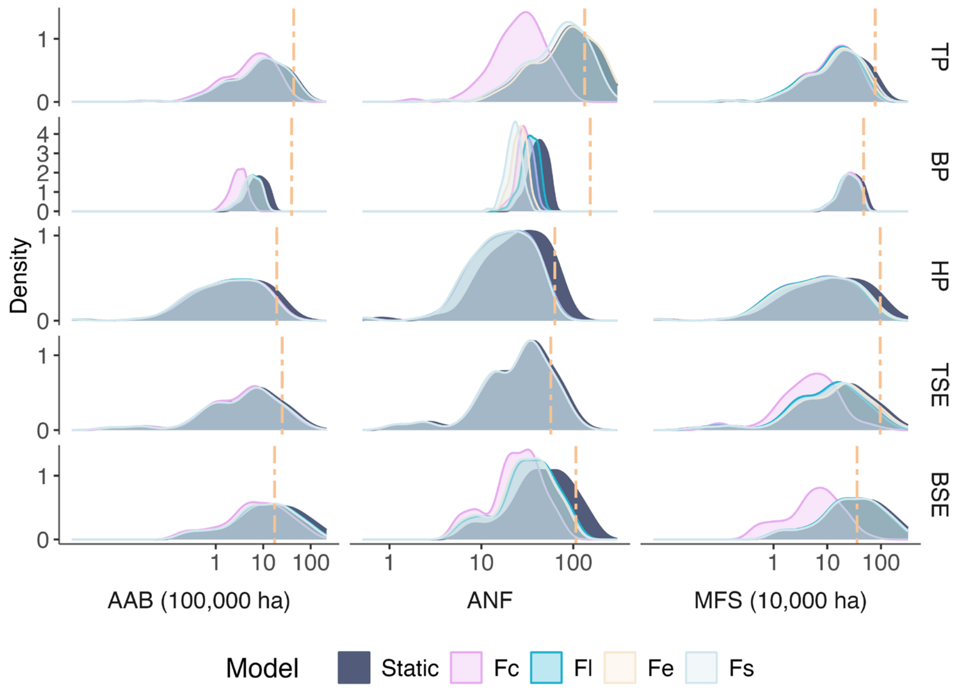

FIGURE 5 | Illustration of how extreme the 2023 fire season is by the end of this century. Density curves show the distributions of annual area burned (AAB), annual number of fires (ANF) and annual maximum fire size (MFS) projected by static and dynamic models in the 2080s under the RCP8.5 scenario. Vertical dashed lines indicate the fire activity of the 2023 fire season. Only ecozones with unprecedented area burned in 2023 were presented. See Figures S9, S10 for RCP2.6 and RCP4.5.

processes from our models. In addition, our models did not account for fuel enhancement triggered by fires or climatic factors, such as forest encroachment and expansion induced by infrequent burning (Keane et al. 2002), higher forest productivity in response to a warming climate (Price et al. 2013) and increasing fuel loads and flammability due to altered forest structure post fires (Tiribelli et al. 2018), which may counteract the effects of fuel limitations. These complicated mechanisms of fire-fuel feedback are beyond the scope of this study and may warrant future analysis.

The comparison with the record-breaking fire year of 2023 suggests that such extreme fire seasons may become more common though not highly frequent in the future. By the end of this century, even with consideration for fire-fuel feedback, seasons with comparable area burned are estimated to occur with a probability of about 11.4% under the most severe scenario for ecozones that experienced unprecedented area burned in 2023, with a higher probability of 25.1% in the eastern ecozones. This result complements previous findings indicating that seasons reaching the peak fire weather intensity observed in 2023 would be about 1.6 times more likely to occur in a 2°C warmer world in eastern Canada (Barnes et al. 2023). In our study, future years with fire extent (annual area burned and annual maximum fire size) exceeding 2023 are projected to be more prevalent than those with greater fire occurrences (annual number of fires). This aligns with projected changes in fire activity and underscores the extraordinary characteristics of the 2023 fire season (Kirchmeier-Young et al. 2024; Jain et al. 2024; Jones et al. 2024), which was marked by burned area more than seven times the historical national average, with the number of fires comparable to the recent fire history. The higher likelihood of more extreme years in the eastern region was attributable to projected increases in fire extent, highlighting the need for greater attention and concern.

This research provides the first national-scale quantitative assessment of the feedback effects of fire-induced fuel reduction on subsequent fire extent and frequency across Canada. It offers critical insights into the complex interactions between climate change and fire dynamics. Incorporating fire-fuel feedback to rectify projections of future fire activity enhances future fire threat evaluations, which are essential for effective forest management and conservation strategies (Bowman et al. 2009, 2020; Flannigan et al. 2006, 2009). Understanding spatial variability in fire-fuel feedback effects allows policymakers and stakeholders to tailor region-specific mitigation and adaptation measures. Ultimately, this study contributes to a more nuanced understanding of how climate change will shape fire activity across Canadian forests, informing efforts to preserve biodiversity, protect carbon stocks and ensure the resilience of natural landscapes in the face of escalating fire conditions (Flannigan et al. 2006, 2009). Future studies could explore how other aspects of fire regimes, such as fire intensity and burn severity, respond to the fire-fuel feedback. Such aspects are critical to fully capturing regional fire variability and the corresponding socio-ecological consequences. Moreover, the effects of fire-fuel feedback may vary profoundly, spanning different spatial units or analysis scales, which are highly uncertain and need more exploration. These investigations are expected to have instructive implications for contextualising the complicated multiscale fire–climate–vegetation interplay.

Author Contributions

Xianli Wang, Weiwei Wang and **Guangyu Wang:** conceptualisation. **Weiwei Wang, Xianli Wang, Tom Swystun,** and **Tongli Wang:** methodology. **Weiwei Wang, Xianli Wang** and **Guangyu Wang:** investigation. **Weiwei Wang:** visualisation. **Guangyu Wang** and **Xianli Wang:** supervision. **Weiwei Wang:** writing and original draft. **Weiwei Wang, Xianli Wang, Jacqueline A. Oliver, Tongli Wang, Tom Swystun, Mike D. Flannigan, Wanli Wu, John L. Innes**, and **Guangyu Wang:** writing and review and editing.

Acknowledgements

We thank Dr. Nicholas C. Coops from the Integrated Remote Sensing Studio, Faculty of Forestry, University of British Columbia, for his insightful comments on the manuscript. The authors also thank Kathryn Levesque from the Northern Forestry Centre, Canadian Forest Service, for proofreading. We acknowledge funding for this research from the APFNet-UBC National Park Research Project (APFNet 2017 Sp2-UBC). Open Access funding provided by the Natural Resources Canada library.

Funding

This work was supported by APFNet-UBC National Park Research Project, APFNet 2017 Sp2-UBC.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The National Burned Area Composite (NBAC) dataset and the National Fire Database (NFDB) are available from http://cwfis.cfs.nrcan.gc.ca/datamart. The MODIS and VIIRS hotspots used to derive daily fire growth data from 2001 to 2023 are available from https://firms.modaps.eosdis.nasa.gov/active_fire/. The fire weather data were obtained from the Canadian historical daily fire weather data provided by the Canadian Forest Service and the fifth phase of the Coupled Model Intercomparison Project (CMIP5) database (Taylor et al. 2012). The R code is available at https://zenodo.org/records/14660012.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** geb70182-sup-0001-supinfo.docx.