Forest Ecology and Management 598 (2025) 123180

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Snow dynamics and forest structure interact to increase wildfire burn severity in the boreal forest

Jack A. Goldman [a,*], Marie-Josée Fortin [b], Patrick M.A. James [a]

[a] Institute of Forestry and Conservation, John H. Daniels Faculty of Landscape, Architecture and Design, University of Toronto, 33 Willcocks St., M5S 3B3, Toronto, ON, Canada

[b] Department of Ecology and Evolutionary Biology, University of Toronto, 25 Willcocks St., M5S 3B2, Toronto, ON, Canada

ARTICLE INFO

Keywords:
Snow cover
Climate change
Burn severity
Boreal forest
Ontario
Structural equation model

ABSTRACT

Climate change in boreal regions is leading to warmer, drier conditions which amplify wildfire activity by altering fuel moisture, weather conditions, as well as the timing and duration of snow cover. Reduced snowpack and earlier snowmelt can lower fuel moisture, extend wildfire seasons, and increase burn severity. However, the effects of snow cover on burn severity under different environmental conditions remain uncertain. We examined how forest structure and snow cover dynamics affect burn severity using structural equation models and remotely sensed burn severity data from 689 wildfires in Ontario's boreal forest from 2002 to 2019. Longer snow-free periods were associated with more extreme burn severity but, contrary to our expectations, lower median severity. Earlier snowmelt also decreased median severity. Forest structure indirectly affected burn severity through snow disappearance date and snow-free duration, but directly influenced only extreme cases. In Ontario's western ecoregion, these factors had a stronger impact compared to the eastern ecoregion where with the length of the snow-free period had the most significant effect on burn severity. Our findings suggest that earlier snow disappearance and longer snow-free periods, driven by ongoing climate change, is increasing the likelihood of extreme burn severity.

1. Introduction

In 2023, Canada experienced the most severe wildfire season in the country's history with 18.4 Mha of land burned. This burn extent is nine times larger than the historical average of 2.1 Mha burned per year from 1959 to 2015, and more than double the previous annual record of ~8 Mha burned in 1989 (Hanes et al., 2019; Harvey, 2023). Although the increasing magnitude of modern wildfires is often attributed to more extreme weather or longer wildfire seasons (Hanes et al., 2019; Jain et al., 2024, 2017; Wotton et al., 2017) an often overlooked driver of wildfire activity is changes in the depth and duration of snow cover (Parisien et al., 2023). Indeed, recent studies have linked earlier snow disappearance dates (hereafter SDDs) over the last few decades (Mudryk et al., 2018) to increases in the number of wildfire ignitions across the boreal forest (Hessilt et al., 2024; Parisien et al., 2023), longer fire seasons (Jain et al., 2017), and overall increases in wildfire activity (i.e., frequency and extent) (Hanes et al., 2019). Moreover, burn severity is expected to increase in the boreal forest in the coming decades (Wang, 2024). Burn severity refers to the degree of vegetation change or loss following a wildfire and is an indication of the degree to which an area has been altered by wildfire (Keeley, 2009; Key and Benson, 2006). Because burn severity reflects both the post-fire state of an ecosystem and the ecosystem's ability to recover to its pre-disturbance state (Baltzer et al., 2021), changes in wildfire burn severity are of particular concern for conservation and forest management. Yet, despite the clear relationship between snow cover and fire season length, few studies have investigated how changing snow cover dynamics might influence wildfire severity in seasonally snow-covered regions like the boreal forest.

One of the major drivers of burn severity in boreal regions is fuel moisture (Parks et al., 2018; Whitman et al., 2018). Fuel moisture determines fuel availability and ignitability during the fire season (Ellis et al., 2022) and is closely related to SDD. Litter (i.e., surface) fuels on the forest floor tend to dry out following snowmelt and then regain their moisture during the cool season (Estes et al., 2012). For this reason, the timing of peak fuel moisture is synchronous with the SDD (Harpold et al., 2015). An earlier SDD causes reduced spring and summer fuel moisture, thus enhancing fire ignitions in areas that are not fuel-limited

* Corresponding author.
E-mail address: jack.goldman@mail.utoronto.ca (J.A. Goldman).

https://doi.org/10.1016/j.foreco.2025.123180
Received 31 January 2025; Received in revised form 10 September 2025; Accepted 12 September 2025
Available online 31 October 2025

(Gergel et al., 2017). For example, in the western United States, earlier spring snowmelt is correlated with reduced summer fuel moisture and increased burn severity (Westerling et al., 2006). Because snow accumulation and ablation amounts vary between years and across regions, SDD—and therefore peak fuel moisture—can vary by several weeks (Estes et al., 2012; Ellis et al., 2022). In Canada, climate change has been driving long-term decreases in snow cover extent and duration (Derksen et al., 2019; Gottlieb and Mankin, 2024). Overall, a longer snow-free duration (i.e., days between snow disappearance date and wildfire ignition date, hereafter SFD) and earlier SDD will affect the rate at which fine fuels dry out in the spring, the level of fuel moisture over the entire fire season, and consequent wildfire burn severity.

Burn severity is also affected directly and indirectly by forest structure (i.e., the three-dimensional variation in age, canopy height, and biomass throughout a forest stand). Forest structure directly influences burn severity by determining the amount of available biomass to burn and the connectivity of fuels at both the stand and landscape scales, as well as across forest vertical strata (Kane et al., 2015). Forest structure can also indirectly affect burn severity through its effects on snowpack amount and SDD. In dense forest stands, the forest canopy intercepts snow and thus reduces snowpack (Balland et al., 2006). Dense canopies also dampen solar radiation, reducing snow ablation rates and promoting longer snowpack retention (Varhola et al., 2010). In contrast, open forest stands, such as those composed of jack pine (*Picea banksiana*), have sparse canopy cover and more space between trees, leading to greater snow accumulation (Pomeroy et al., 2002). These region- and forest structure-dependent changes in snowmelt timing further affect the drying rates of litter fuels and contribute to water stress throughout the fire season. However, the indirect effects of forest structure on burn severity, as mediated by snow cover dynamics, remain poorly understood.

Here, we investigated how snow cover dynamics affect wildfire burn severity across different ecoregions with varying climates and forest structures in the boreal forest of Ontario, Canada. Using remotely sensed data, we quantified forest structure (including crown closure, aboveground biomass, and stand age), snow cover dynamics (including SDD and SFD), and burn severity for a series of wildfires that occurred in Ontario's boreal shield ecozone between 2002 and 2019 (Fig. 1). To isolate the effects of forest structure and snow cover dynamics, we also controlled for the influences of drought conditions and topography (Fig. 2a), which are known to affect both burn severity and snow cover.

We test three core hypotheses about the relationship between snow cover dynamics and burn severity using structural equation models (SEMs): (1) an earlier SDD and longer SFD will increase median and extreme burn severity by decreasing fuel moisture; (2) forest structure will have a more significant effect on burn severity than SDD and SFD; and (3) the strength of these effects will vary across our different study ecoregions. Overall, a better understanding of these relationships will equip forest managers with insights into the emerging interplay between forest structure, snow cover dynamics, and fire, enabling them to develop strategies to reduce overall burn severity in the face of decreasing snow resources.

2. Methods

2.1. Study area

From 2008–2018, over one-third of Canada's boreal forest wildfires occurred in Ontario's boreal shield ecozone (Fig. 1) (Coops et al., 2018). This ecozone is divided into two ecoregions: the drier west and the more humid east (Beverly and Martell, 2005). The west features open stands of jack pine, while the east has dense stands of black spruce (*Picea mariana*). Studies often contrast these two ecoregions due to their differing climates, forest structures, and corresponding wildfire dynamics (Beverly and Martell, 2005; James et al., 2017). In our case, the biophysical gradient from east to west allowed us to test how the relationships between snow cover and burn severity varied across the study area (Fig. 3).

2.2. Fire data

We obtained wildfire occurrence and extent data for 2002–2019 from Ontario's Fire Disturbance Area database (Ontario Ministry of Natural Resources and Forestry, 2021). Our study focused on fire events from 2002 to 2019, as this was the only period with consistent overlap in data for snow cover, weather, and forest structure. We excluded

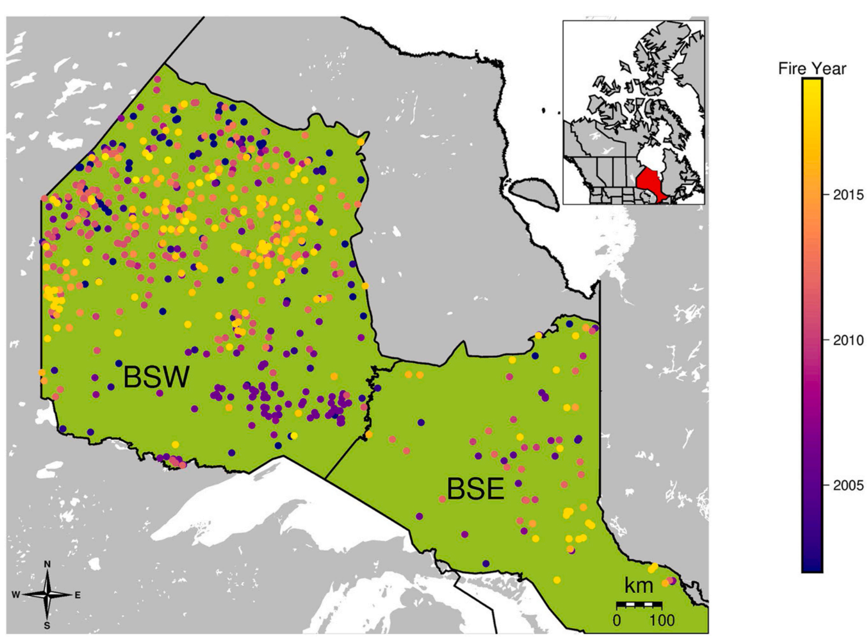

Fig. 1. Map of wildfires that burned in the boreal shield ecozone of Ontario between 2002 and 2019 ($N = 689$) demoted as circles. BSW denotes the western boreal shield ecoregion (boreal shield west). BSE denotes the eastern boreal shield ecoregion (boreal shield east). Colors represent the year of the fire. Fire locations are represented as the centroid of the corresponding fire perimeter.

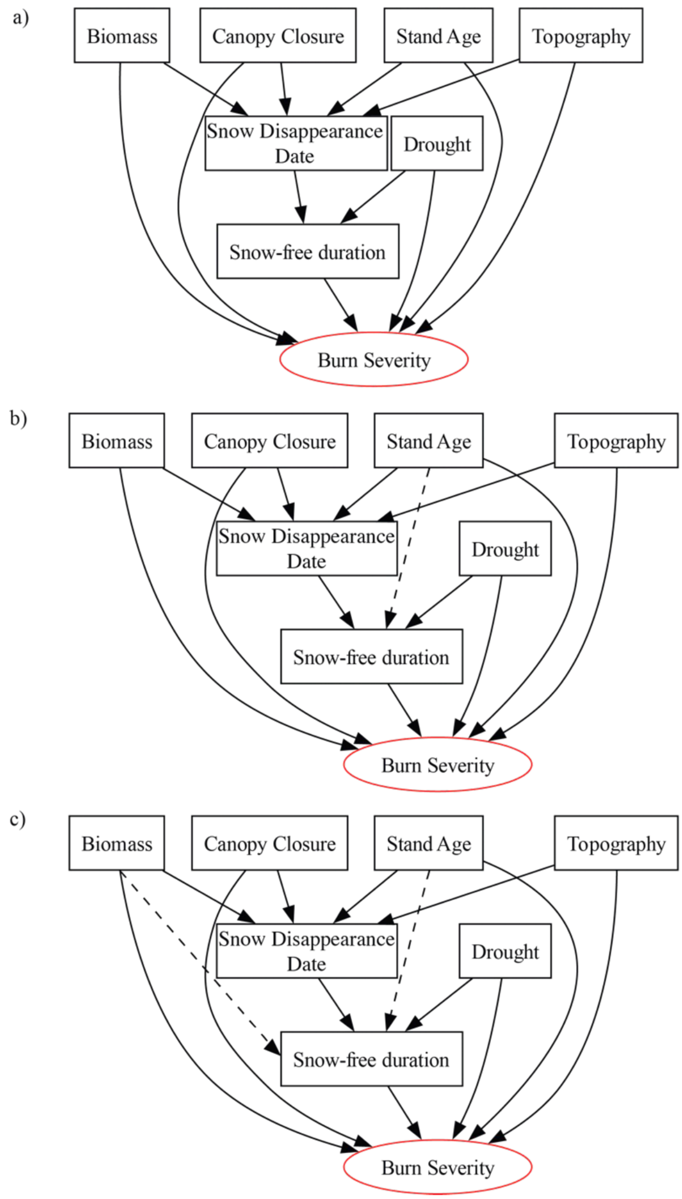

Fig. 2. Directed acyclic graphs representing hypothesized causal relationships among forest structure, snow dynamics, and fire severity. A) Our *a priori* model of hypothesized causal relationships among all variables. B) Updated causal relationships based on structural equation models estimating burn severity for all fires across the entire boreal shield. C) Updated causal relationships estimating within-fire variability in burn severity. Solid lines represent pathways specified in the initial *a priori* model, and dashed lines represent additional pathways between biomass and snow-free duration and stand age and snow-free duration that were identified in tests of directed separation.

prescribed burns as well as reburns (fires in previously burnt areas), which can show significant variation in burn severity relative to areas without recent wildfires (Whitman et al., 2022). We also excluded fires if the overlap between two fire polygons exceeded the smallest burned area in our dataset (40 ha). A fire polygon refers to the fire perimeter, encompassing the entire area affected by a fire. The entire area covered by the fire polygon, including unburned residuals within the fire polygon, were included in the analysis with the exception of all water bodies, which were excluded from the analysis. After these filtering steps, 689 fires remained for analysis, covering a total area of 1996,403 ha or 3 % of Ontario's boreal shield ecozone. We categorized these fires into three size classes based on established thresholds for fire size in Canada's boreal forest (Stocks et al., 2002): small (< 500 ha; $n = 412$), medium (500–10,000 ha; $n = 253$), and large (> 10,000 ha; $n = 45$). The total area burned per category was 71,711 ha, 635,672 ha, and 1289,020 ha for the small, medium, and large fires, respectively.

2.3. Burn severity calculation

We measured burn severity for each fire using the relativized burn ratio (RBR), a Landsat-based metric that quantifies fire-related changes in forest cover relative to the pre-fire vegetation. The RBR metric is more robust than other Landsat-based measures (e.g., RdNBR) because it is more sensitive to pre-fire normalized burn ratio (NBR) values in areas where vegetation cover is low (Parks et al., 2014a). The RBR is calculated by dividing the delta normalized burn ratio (dNBR) by the pre-fire normalized burn ratio (NBR) (see Supplementary Materials). Remotely sensed burn severity data for each fire were obtained at a 30 m resolution using Google Earth Engine. We then generated burn severity maps from Landsat TM, ETM+ and OLI imagery using a hybrid mean-compositing approach developed for the boreal region (Holsinger et al., 2021), which averages pre-fire and post-fire imagery.

We summarized pixel-based measures of burn severity within each

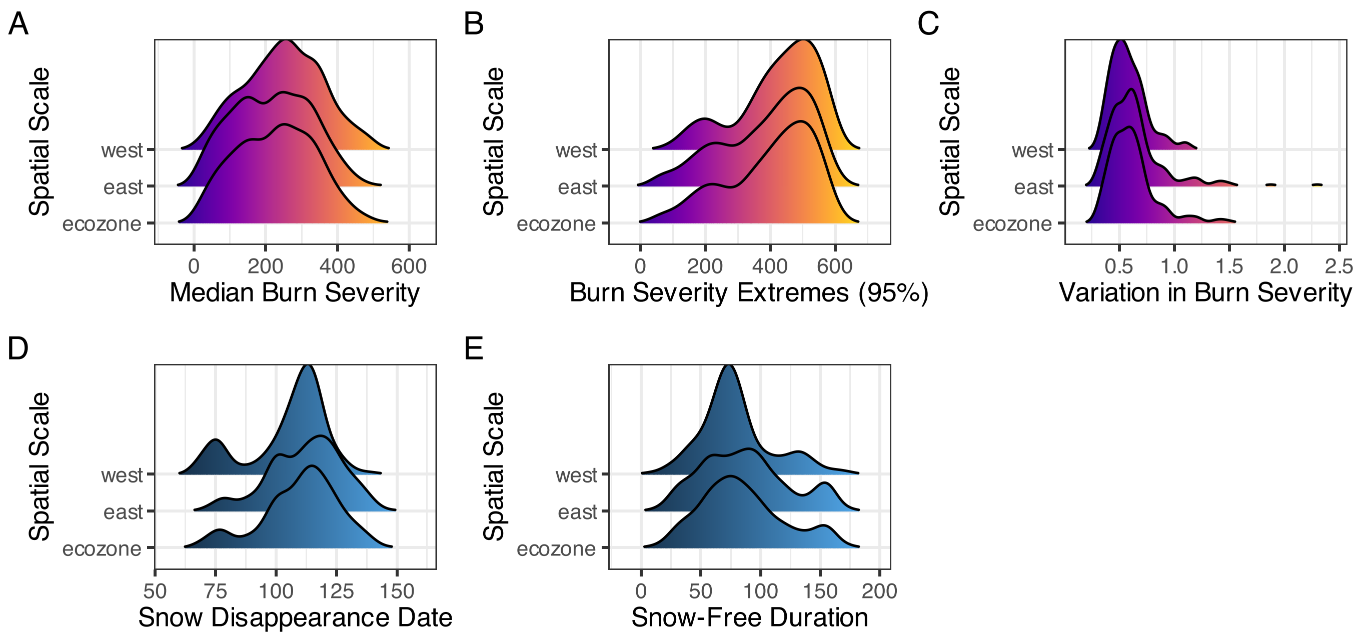

Fig. 3. Ridgeline plots depicting the distribution of five different variables related to burn severity and snow conditions across three ecoregions: West ecoregion, East ecoregion, and the entire ecozone. The variables shown are: (A) median burn severity; (B) burn severity extremes; (C) coefficient of variation; (D) snow disappearance date; (E) snow-free duration. Each plot provides a visual representation of the data distribution for these critical environmental metrics across different ecoregions.

fire polygon using two separate metrics: the median and 90th percentile RBR. The median RBR has been used in the past to model burn severity and represents generalized severity across the burn area (Parks et al., 2014b), whereas the 90th percentile RBR captures extreme burn severity within the fire polygon. Most studies quantify or distinguish high burn severity by categorizing pixels into high, moderate, or low severity using the Composite Burn Index (CBI) to provide empirically validated (supervised) break points for these different categories (Whitman et al., 2020). However, because there are no field-based reference (CBI) data currently available for Ontario, we used the 90th percentile to capture fires that may have burned at a higher overall severity.

2.4. Snow cover data

To quantify snow cover dynamics across our study area, we determined the snow disappearance date (SDD) and snow-free duration (SFD) for each fire polygon. The SDD is the last day of the year that snow was detected within a fire perimeter. We used NASA's global, 500 m resolution daily snow cover product (MODIS/Terra MOD10A1 v6.1) and Google Earth Engine to generate SDD maps using a method developed for the Northern Hemisphere (Crumley et al., 2020). These maps covered the entire Ontario boreal shield and were used to calculate the mean SDD within each fire polygon.

The SFD for each fire was then calculated as the number of days between the mean SDD within the fire polygon and the date of ignition. The date of ignition was determined in Google Earth Engine based on MODIS Terra and Aqua Thermal Anomalies and Fire Daily Global datasets (MOD14A1 V6.1 and MYD14A1). Specifically, the MODIS fire product provides daily imagery at a 1-km resolution, and we determined the date of ignition by identifying when burned pixels were first detected within the fire perimeter by modifying a previous method that determined when no burned pixels were detected within a fire perimeter (Holsinger et al., 2021).

2.5. Forest structure data

We chose three variables to represent forest structure: stand age (years), canopy closure (%), and total average biomass (tons per hectare). These metrics were chosen because they influence both snow cover and burn severity in the boreal forest (Davis et al., 1997; Halim et al., 2019; Whitman et al., 2018). Stand age is a fundamental component of forest structure, influencing various structural attributes such as canopy closure and biomass (Bergeron et al., 2017; Fricker et al., 2013). Remotely sensed forest structure data were derived using MODIS at a 250 m spatial resolution. Values for each fire polygon were then calculated by averaging the values of all pixels within the fire perimeter. Due to the limitations of the MODIS data, we only used forest structure information from 2001 and 2011 (Beaudoin et al., 2017). For fires that occurred between 2002 and 2011, we used the 2001 data for canopy cover and biomass, and for fires after 2011, we used the 2011 data. This approach assumes that in the absence of stand-replacing disturbances, canopy cover and biomass remained constant from 2001 to 2010 and from 2011 to the end of the study period. However, we used the MODIS data and the fire year to calculate stand age at the time of each fire.

Although species composition also affects boreal fire severity (Rogers et al., 2015), we excluded species composition from our analysis to focus more narrowly on the role of forest structure on both snow cover and burn severity. Indeed, the impact of species composition on wildfire behavior is mainly driven by differences in species-specific structural attributes between fuel types (Ryan, 2002). These attributes include the forest structure variables we measured (e.g., canopy closure, biomass, and age), which determine the connectivity and flammability of forest stands. Summary statistics of these metrics across our study area are shown in Table S1.

2.6. Topography

Topography influences both wildfire severity (Taylor et al., 2021) and snowmelt (Heldmyer et al., 2021). We accounted for topographic variation using the terrain ruggedness index (TRI) (Riley et al., 1999). The TRI represents the mean elevation difference between adjacent cells in a 30 m resolution digital elevation model. Higher TRI values indicate more rugged or complex terrain, whereas lower TRI values suggest flatter areas. First, we calculated TRI for each pixel in a fire perimeter using the Canadian Digital Elevation Model (CDEM) provided by Natural Resources Canada (Natural Resources Canada, 2024) in Google Earth Engine. We then calculated the mean TRI within each fire perimeter to be used in all subsequent analyses.

2.7. Weather data

To account for the effects of weather on burn severity following snowmelt, we used the drought code (DC). Initially developed by Turner et al. (1972) and later modified by Van Wagner (1987). DC is a fire weather index used within the Canadian Forest Fire Behaviour Prediction system. It quantifies drought by rating the average moisture content of deeper forest soils (Van Wagner, 1987), thereby capturing the effects of drought and reduced vegetation moisture on wildfire burn severity (Talucci et al., 2022; Talucci and Krawchuk, 2019; Whitman et al., 2018). DC is analogous to the vapour pressure deficit (VPD), which also captures moisture stress in boreal soils and vegetation. We chose DC over VPD because it was specifically developed for assessing fuel moisture in the eastern boreal forest (Ryan, 2002; Van Wagner, 1987). We interpolated the DC at the centroid of each fire perimeter on the day of ignition using thin plate splines, a common method for interpolating fire weather indices (Jain and Flannigan, 2017). This interpolation was based on data from weather stations across our study region.

2.8. Spatial resolution

One challenge with using remotely sensed data was that the data products we used were generated at different spatial resolutions: burn severity and topography data were derived from 30 m resolution sources, forest structure data from 250 m resolution sources, snow cover from 500 m resolution sources. We summarized each data product over the burn area by averaging the values of all pixels within each fire perimeter. The only exceptions to this approach were burn severity, for which we calculated the median and 90th percentile of all values, and the drought code, which we interpolated as described above. These summarized values for each fire perimeter were used for all subsequent analyses.

2.9. Statistical analyses

We examined the direct and indirect effects of SDD, SFD, and forest structure on burn severity using piecewise structural equation modeling (SEM; (Lefcheck, 2016)). Compared to traditional variance-covariance structural equation modeling, piecewise SEM is more effective at handling data that do not conform to assumptions of multivariate normality and correlated error structures, which are common in spatial environmental data (Lefcheck, 2016). This approach enabled us to assess: (1) the direct effects of forest structure on SDD and SFD; (2) the direct effects of SDD and SFD on burn severity; and (3) the indirect effect of forest structure on burn severity, as mediated by the forest structure-related effects on SDD and SFD.

2.9.1. Model structure

The modelling process began by defining an *a priori* model of the causal relationships between pairs of variables (Fig. 2a). We hypothesized that forest structure—represented by mean aboveground biomass, mean stand age, and canopy closure—directly affects SDD and SFD (Figure S1) by increasing canopy interception, ablation, and sublimation. Forest structure also directly influences burn severity by altering fuel availability. Our model also included a path from DC to SFD, as drought conditions enhance fuel flammability, it will increase the likelihood of ignition, and earlier fire ignition would reduce SFD (Hanes et al., 2020; San-Miguel et al., 2020). This hypothesized *a priori* causal model served as a general test of how forest structure moderates the effects of SDD and SFD on wildfire burn severity (for both median and 90th percentile).

Within the piecewise SEM framework, we fit linear mixed effects models using the "nlme" package in *R* version 4.3.0 (Pinheiro et al., 2023; R Core Team, 2023). Models were fit with maximum-likelihood estimation to allow for the comparison of models with different fixed effect structures using likelihood ratio tests, which is crucial in SEM for testing hypotheses about the relationship between variables (Shipley, 2016). The predictors in our analyses included SDD, SFD, stand age, canopy closure, total aboveground biomass, topography (TRI), and drought (DC). We included random intercepts for fire size class (small, medium, or large) nested within fire year (2002–2019) to account for variations in fire size and yearly differences. Because the 90th percentile burn severity was left-skewed, we used a square-root transformation to normalize model residuals. We further assessed multicollinearity by calculating the variance inflation factor (VIF) for each set of regressions before fitting the piecewise SEM, using a threshold value of VIF > 0.8 (Zuur et al., 2010). Based on the VIF analysis, no predictors needed to be excluded from the model. Model assumptions (i.e., normality, homoskedasticity) were verified by conducting a visual inspection by plotting residuals against fitted values, and against each covariate in the model. We further verified normality by inspecting a histogram of residuals.

2.9.2. Model fit and performance

We measured the strength of all modeled direct, indirect, and total effects using standardized regression coefficients. Direct effects were quantified as the strength of the pathway between a parent (cause) and its immediate child (effect). Indirect effects were quantified as the product of all the standardized regression coefficients between a parent and a child in cases where the parent was not directly connected to the child (Shipley, 2016). We additionally assessed the overall model goodness of fit using Shipley's test of directed separation and Fisher's *C*-statistic for piecewise SEM (Shipley and Douma, 2020). The test of directed separation evaluates whether the empirical data support the hypothesized causal relationships in the model (Fig. 2a) and Fisher's *C*-statistic measures how well the causal model fits the data, with lower values indicating a better fit.

2.9.3. Effects of ecozone and ecoregion level

To assess how ecozone and ecoregion level influenced the strength of our hypothesized causal relationships, we built separate SEMs at three different scales and then compared the strengths of the standardized regression coefficients. Specifically, we tested our hypothesized causal structure on the entire Ontario boreal shield ("ecozone scale", $n = 689$) and then separately on the east ($n = 76$) and west ($n = 613$) ecoregions ("ecoregion scale"). This approach also allowed us to account for the potential confound of different forest species composition between the east and west ecoregions.

To investigate whether the indirect effects of forest structure on burn severity differed between the east and west ecoregions, we conducted a multigroup analysis with the two ecoregion SEMs (Douma and Shipley, 2021). First, we fit an overall SEM for each of the four ecoregion $\times$ response combinations (median and extreme burn severity in the east and west), allowing all path coefficients to be estimated as free parameters. We then fit subsequent piecewise SEMs (pSEMs)for each indirect pathway from forest structure variables (i.e., canopy closure, biomass, stand age) to burn severity. We fixed the path coefficients to 0 of all the paths along the indirect pathways of interest by ecoregion. Since the path coefficients represent the relationship between variables, setting the path coefficient to 0 for certain groups assumes that there is no relationship between those variables for those specific groups. For example, for the indirect causal pathways between stand age and burn severity, we fixed the paths from stand age to SDD and SFD and from SDD and SFD to burn severity. Using a previously developed method, we calculated how the paths differ by ecozone or ecoregion for each pathway of interest by comparing the difference of the summed chi-square and summed degrees of freedom between fixed path and original models to a chi-square distribution (Douma and Shipley, 2021).

If the p-value was greater than $\alpha = 0.05$, we concluded that the indirect pathway differs between the two ecoregions.

2.9.4. Variation in burn severity

To capture the considerable variability in fire severity that may occur within a single fire (Cansler and McKenzie, 2014), we calculated the coefficient of variation for burn severity within each fire perimeter. Using this measure and piecewise SEM, we tested whether changes in SDD and SFD affect heterogeneity in burn severity within individual fires. Only fires greater than 500 ha were included in this analysis because larger fires exhibit greater within-fire variability in burn severity and more frequently contain larger high-severity patches (Cansler and McKenzie, 2014). This additional test for within-fire variability allowed us to assess whether our causal relationships explained not only median and extreme fire severity, but also diversity in burn severity.

3. Results

Our piecewise structural equation models (pSEM; Fig. 2) allowed us to identify both direct and indirect relationships among forest structure, snow cover dynamics, and wildfire burn severity. In the *a priori* causal model, we did not hypothesize that stand age would affect snow-free duration (Fig. 2a); however, we found evidence of this relationship and subsequently updated the causal model to include this pathway (Fig. 2b). The ensuing model was used to model both median and extreme severity across the entire boreal shield region (Fig. 2b), yet for each ecoregion we modeled median and extreme severity using our original causal model (Fig. 2a). Furthermore, we found that the appropriate causal model for within-fire variation in burn severity differed from models for median and extreme burn severity because it included a pathway between biomass and SFD that was not included in our *a priori* model (Fig. 2c).

Our directed separation tests additionally revealed that these causal relationships differed between measures of severity. Furthermore, these causal relationships differed between the ecozone and ecoregion scales. At the ecozone scale, our models explained more variation in SFD than SDD and more variation in extreme than median burn severity (Table 1). However, the causal model with the most explanatory power (i.e., highest R^2) for burn severity at the ecozone scale was the model that estimated within-fire variability in burn severity using only fires larger than 500 ha (Table 1). At the ecoregion scale, the causal model for both median and extreme burn severity fit the data better in the eastern ecoregion than the western or ecozone models, as indicated by a lower Fischer's C-Statistic (Table 1). The causal model for the eastern ecoregion explained the most variation in SDD, SFD, and median and extreme burn severity (Table 1). All relationships between predictors and response variables were linear and we verified that model assumptions of normality were met for all models.

3.1. Direct effect of forest structure on snow disappearance date and snow-free duration

With respect to the effects of individual predictors, we found that the direct effect of forest structure on SDD and SFD varied between the eastern and western regions. Forest biomass (average tonnes per hectare within a fire perimeter) had a significant negative effect on SDD at the ecozone scale and in the eastern boreal shield but not in the western ecoregion (Table 2). In contrast, canopy closure had a significant negative effect on SDD in the western ecoregion but not in the east or at the ecozone scale (Table 2). Stand age had a significant positive effect on SDD in all ecozone and ecoregion models except the model considering only fires larger than 500 ha (Table 2).

Forest structure variables had weaker and less consistent effects on SFD across all models. Stand age had a significant positive effect on SFD in the ecozone model, and this effect was greatest in the model for > 500 ha fires (Table 2). Biomass had a significant negative effect on SFD, but this relationship only appeared in the model for > 500 ha fires (Fig. 2c; Table 2). The relationship between canopy closure and SFD did not appear in any model.

3.2. Direct effects of forest structure, snow disappearance date and snow-free duration on wildfire burn severity

One of our focal hypotheses was to assess the direct predictors of burn severity. At the ecozone scale, the strongest direct predictor of burn severity was SFD, with weaker effects of forest structure and SDD. This result held true in the western ecoregion but not the eastern ecoregion, where we observed no direct effect on either measure of burn severity (Table 2). Interestingly, SFD had a positive effect on 90th percentile burn severity but a negative effect on median burn severity (Table 2, Fig. 4a). In contrast, SDD was only a significant predictor for median burn severity at the ecozone scale, where it had a negative effect.

Forest structure was a significant predictor for extreme but not median burn severity in only the ecozone and western ecoregion models. Specifically, biomass had the strongest effect on burn severity at the ecozone scale, whereas canopy closure had the strongest effect in the west. In both cases, forest structure positively influenced burn severity (Table 2). Interestingly, these effects were reversed in the corresponding models: biomass and canopy closure each had negative effects on burn severity in the western and whole-ecozone models, respectively. In the model estimating within-fire variability in burn severity, SFD had a significant positive effect on within-fire variation that was stronger than the negative effect of stand age. Neither SDD nor the remaining forest structure metrics were significant predictors of burn severity.

3.3. Indirect effects of forest structure on wildfire burn severity

We additionally used our piecewise SEM framework to identify the indirect effects of forest structure on median and extreme burn severity. As expected, the indirect effects were weaker than the direct effects because they result from the product of the standardized regression coefficients of two or more adjacent paths. At the ecozone scale, biomass and stand age had positive and negative effects, respectively, on burn severity, though both effects were similar in magnitude (Figure S). However, the indirect effects of canopy closure and topography on burn severity were negligible (Figure S5).

These indirect effects of forest structure were qualitatively similar across the two ecoregions and both measures of burn severity, with stand age having the strongest indirect effect in the western ecoregion (Figure S5). We conducted a multigroup analysis to determine if these indirect causal pathways between forest structure and burn severity differed quantitatively between the two ecoregions. Based on the

Table 1
Model fit for all structural equation models that we evaluated. C values, degrees of freedom (df), and p-values are associated with Fisher's C-statistic and $p > 0.05$ indicates a stronger fit, and the R^2 values represent the proportion of variation that each model explained for the following variables: sdd = snow disappearance date; sfd = snow-free duration; sev = severity (measured as the 90th percentile burn severity, median burn severity, or the coefficient of variation in burn severity within a fire polygon, as denoted in the response column).

Response	C	df	p	R^2 (sdd)	R^2 (sfd)	R^2 (sev)
Entire Boreal shield						
Extreme	14.177	8	0.077	0.67	0.84	0.20
Median	14.177	8	0.077	0.67	0.84	0.12
Variability	6.069	6	0.415	0.77	0.90	0.29
Western Boreal shield						
Extreme	15.695	10	0.109	0.66	0.84	0.21
Median	15.695	10	0.109	0.66	0.84	0.14
Eastern Boreal shield						
Extreme	11.308	10	0.334	0.73	0.90	0.29
Median	11.308	10	0.334	0.73	0.90	0.30

Table 2
Comparison of the direct effects from piecewise structural equation models for both extreme and median burn severity for the entire boreal shield, western boreal shield, and eastern boreal shield. The table compares the coefficient estimates and significance of direct effects for each pathway. In instances where no values are shown, that specific pathway was not included in the model. SDD = snow disappearance date; SFD = snow-free duration. Significance evaluated at $p < 0.05$.

		Burn Severity Extremes						**Median Burn Severity**						**Within-fire Variability in Burn Severity**	
		Entire Boreal Shield		**Western Boreal Shield**		**Eastern Boreal Shield**		**Entire Boreal Shield**		**Western Boreal Shield**		**Eastern Boreal Shield**		**Entire Boreal Shield**	
Response	**Predictor**	***Std. Estimate***	***p***	***Std. Estimate***	***p***	***Std. Estimate***	***p***	***Std. Estimate***	***p***	***Std. Estimate***	***p***	***Std. Estimate***	***p***	***Std. Estimate***	***p***
SDD															
	Biomass	−0.221	0.001	−0.109	0.117	−0.376	0.022	−0.221	0.001	−0.109	0.117	−0.376	0.022	−0.185	0.070
	Stand Age	0.266	< 0.001	0.261	< 0.001	0.339	< 0.001	0.266	< 0.001	0.261	< 0.001	0.339	< 0.001	−0.120	0.166
	Canopy Closure	−0.082	0.166	−0.208	0.002	0.103	0.513	−0.082	0.166	−0.208	0.002	0.103	0.513	0.296	< 0.001
	Topo	−0.059	0.022	−0.020	0.020	−0.034	0.635	−0.059	0.022	−0.020	0.020	−0.034	0.635	−0.069	0.075
SFD															
	SDD	−0.339	< 0.001	−0.329	< 0.001	−0.487	< 0.001	−0.339	< 0.001	−0.329	< 0.001	−0.487	< 0.001	−0.349	< 0.001
	Drought	0.665	< 0.001	0.600	< 0.001	0.746	< 0.001	0.665	< 0.001	0.600	< 0.001	0.746	< 0.001	0.678	< 0.001
	Stand Age	0.044	0.014	-	-	-	-	0.044	0.014	-	-	-	-	0.183	< 0.001
	Biomass	-	-	-	-	-	-	-	-	-	-	-	-	−0.114	0.001
Burn Severity															
	Drought	−0.169	0.007	−0.174	0.007	−0.050	0.805	0.205	0.001	0.224	0.003	0.180	0.193	−0.131	0.205
	SFD	0.397	< 0.001	0.472	< 0.001	0.077	0.704	−0.438	< 0.001	−0.516	< 0.001	−0.118	0.573	0.328	0.006
	SDD	0.001	0.987	−0.013	0.540	0.103	0.551	−0.116	0.041	−0.156	0.011	−0.016	0.693	0.196	0.029
	Topo	−0.037	0.368	−0.063	0.295	0.098	0.45	0.126	0.003	0.133	0.004	0.218	0.104	−0.268	< 0.001
	Stand Age	−0.151	0.005	−0.187	0.001	−0.154	0.294	0.023	0.675	0.027	0.653	0.068	0.650	0.266	0.004
	Canopy Closure	−0.259	0.005	0.319	0.006	0.378	0.204	0.128	0.192	−0.081	0.462	−0.372	0.161	−0.019	0.910
	Biomass	0.283	0.006	−0.252	0.015	−0.202	0.509	−0.097	0.374	0.059	0.630	0.427	0.238	−0.099	0.488

maximum likelihood chi-squared statistic ($x^2_{L\_ML}$) (Douma and Shipley, 2021), the indirect pathways from biomass and canopy closure to extreme burn severity differed significantly between the east and west ecoregions ($p = 0.296$ and $p = 0.225$, respectively), but the pathway from stand age to extreme burn severity did not ($p < 0.001$). We similarly found between-region differences in the indirect pathways from biomass ($p = 0.219$) and canopy closure ($p = 0.163$), but not stand age ($p < 0.001$), to median burn severity (Figure S6).

3.4. Direct and indirect effects of drought and topography on SDD, SFD, and burn severity

The effect of drought on burn severity varied along the climatic gradient from east to west. Specifically, a higher DC significantly reduced 90th percentile burn severity but increased median burn severity at the ecozone scale and in the western region. However, DC was not a significant predictor in the eastern ecoregion or of within-fire variation. In terms of the impact on snow dynamics, DC had a stronger direct effect on SFD than any forest structure variable or SDD: drought significantly increased SFD in the west, at the ecozone scale, and in the model considering only fires larger than 500 ha (Table 2).

The direct effects of topography on snow cover and burn severity reflected the biophysical differences from east to west. Topography (measured using the TRI) significantly reduced SDD at the ecozone scale for all fires and fires larger than 500 ha, but at the ecoregion scale, this effect was only significant in the west. Topography similarly had a significant positive effect on median severity at the ecozone scale and in the west but not the east. We found no significant relationships between topography and extreme burn severity, whereas topography had a negative effect on within-fire variability in burn severity (Table 2).

Of all the indirect effects we evaluated, the strongest were those of drought on burn severity, which exceeded the indirect effects of both forest structure and topography. Overall, DC was the most influential indirect predictor of burn severity at the ecozone scale, across both ecoregions, and for fires larger than 500 ha. These indirect effects aligned with the direct effects of DC on burn severity: drought had a negative impact on median burn severity and a positive effect on extreme burn severity across all scales (Figures S4, S5). Drought also increased within-fire variability in burn severity (Figure S7).

4. Discussion

Recently, studies have highlighted the crucial effect of snow cover dynamics, and particularly the date of snow disappearance, on wildfire activity in the Canadian boreal forest (Hessilt et al., 2024; Parisien et al., 2023). Indeed, the timing of spring wildfires is largely determined by when the snow melts: earlier SDDs increase wildfire ignitions, whereas later SDDs shorten fire seasons (Hessilt et al., 2024). The effect of snowmelt timing is especially prominent in the eastern boreal forest (Parisien et al., 2023), where snow disappears later in the year relative to other boreal ecozones (Hessilt et al., 2024). Because longer wildfire seasons often create drier conditions and reduce fuel moisture, the timing of snow disappearance and the duration of snow-free periods can therefore affect the intensity and severity of boreal wildfires.

4.1. Snow cover dynamics

We found support for our hypothesis that increases in SFD would increase *extreme* burn severity, but contrary to our expectation, increases in SFD appeared to decrease *median* burn severity (Fig. 4a). We suspect that this SFD-mediated increase in extreme burn severity arises because a longer SFD leads to drier mid-summer conditions. This effect is also reflected in the timing of the fires in our data; indeed, almost half of the fires in our study occurred in July ($n = 324$), and previous studies have shown that burn severity in the boreal shield peaks in July (Guindon et al., 2021). However, an extended SFD might also push fires later in the season, which could explain the observed reduction in median burn severity. This is because fall fires in Canada have been shown to burn with lower severity (Guindon et al., 2021). We additionally found evidence that SFD affects burn severity by causing drought: our

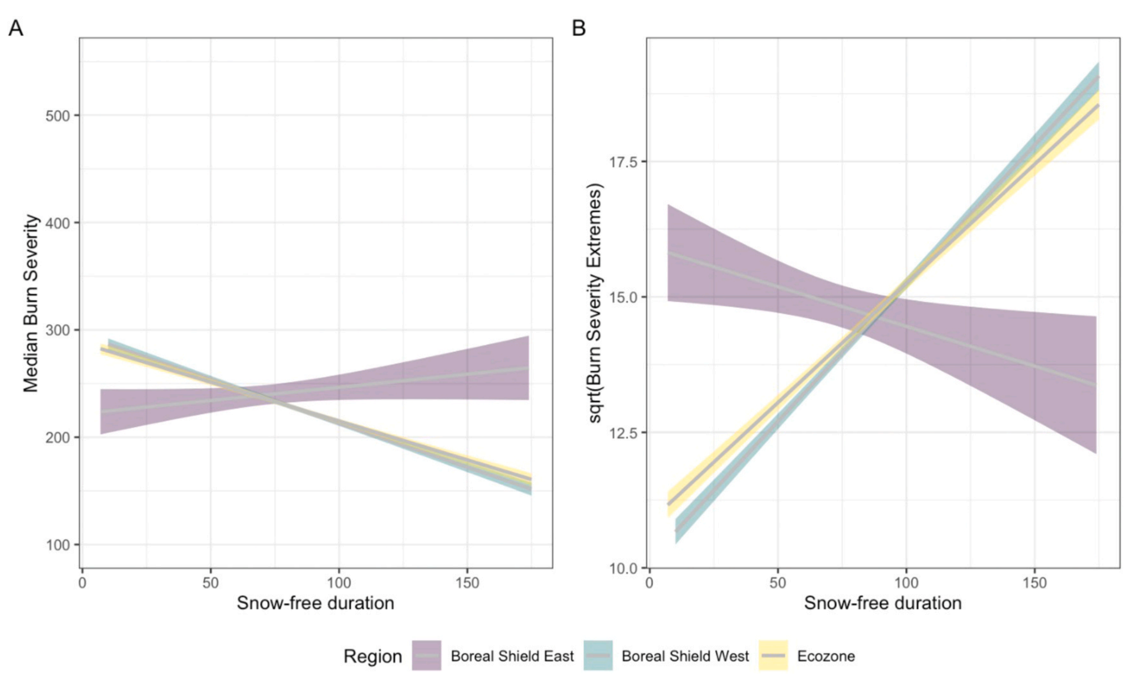

Fig. 4. Marginal effects plots showing the relationships between snow-free duration and A) median and B) extreme burn severity for each of the three model scales we considered. These plots are complementary to the directed acyclic graphs shown in Fig. 2 and demonstrate a simplified version of the relationships between variables. Shaded 95 % confidence intervals were calculated on linear mixed-effects models that were included in the piecewise structural equation model. The 90th percentile burn severity values (i.e., "burn severity extremes") were square-root transformed to the meet assumptions of a linear model (see Methods). Refer to Table S2 for predictor slopes, intercepts, and standard errors.

models showed a consistent positive correlation between SFD and drought, suggesting that drought extended the fire season and may have led to more fires burning in the fall ($n = 169$) when DC is higher. Finally, the relationships between SFD and both median and extreme burn severity, as well as the positive correlation between SFD and drought, were spatially consistent from east to west. This consistency suggests that the direction of the effect of SFD on fire severity remains the same, despite the climatic gradients that differentiate the east boreal shield from the west. To better untangle these complex dynamics, future research is needed to further investigate the mechanisms by which SFD influences both median and extreme burn severity across different climatic regions.

Like SFD, SDD also decreased median burn severity at the ecozone scale and in the west, but unlike SFD, it had no significant effects on extreme burn severity at any scale. These contrasting results can potentially be explained by the effects of forest structure on SDD. Previous work has shown that burn severity decreases with increasing basal area of older trees and increases with overall stem density (Whitman et al., 2018). We found that more aboveground biomass leads to an earlier SDD, but increases in stand age delay it (Figure S5). Furthermore, stand age had a weak but negative indirect effect on median burn severity and biomass had a weak but positive indirect effect, both mediated through changes in SDD. However, the combined SDD-mediated effect of these two forest structure metrics on median burn severity was negative. We interpret this result to suggest that the longer snow remains under the canopy (i.e., a later SDD), the higher the moisture levels in surface and larger-diameter woody fuels (Estes et al., 2012). In turn, elevated fuel moisture reduces burn severity (Whitman et al., 2018).

4.2. Forest structure

Although SFD had a stronger direct effect on burn severity than any of the forest structure variables we considered, we still found some evidence that forest structure directly affects burn severity. These forest structure-related effects were (i) detected for extreme but not median burn severity and (ii) greater in magnitude than the effect of SDD. Together, these results confirm the importance of fuel structure in driving high-severity fires (Parks et al., 2018; Whitman et al., 2018). It has been suggested that recent high-severity fires are driven more by the biomass of live fuels than by fuel drying (Parks et al., 2018). Our results are consistent with this finding, as forest biomass had a strong positive effect on burn severity extremes for all fires and in the western ecoregion (Table 2, Figures S2 and S3). However, trends in general (i.e., median) burn severity in the boreal forest appear to be driven more by SFD and its positive correlation with fuel moisture than by forest structure (Table 2).

Forest structure is known to influence landscape-scale snow cover and snowmelt dynamics through its effect on canopy snow interception and accumulation and subcanopy energy balance (i.e., the exchange of energy, including solar radiation, heat, and moisture, beneath the forest canopy), all of which have been shown to differ between open and closed canopy forests (Dickerson-Lange et al., 2017; Roth and Nolin, 2017). For example, Roth and Nolin (2017) demonstrated that increased canopy cover reduces snow accumulation and increases longwave radiation, collectively leading to earlier snow disappearance. Similarly, greater canopy cover can accelerate snow melt by trapping heat under the canopy (Lundquist et al., 2013).

In the study area, the western boreal shield is dominated by open jack pine stands, whereas the eastern boreal shield is dominated by relatively closed black spruce stands. These ecoregional differences and the interaction between forest structure and subcanopy energy balance likely explain three of our major findings. First, canopy cover in the west was more strongly associated with later snow disappearance (Table 2). Second, the indirect effects of canopy closure and biomass on burn severity differed significantly between the east and west (Figures S5 and S6). Third, we found contrasting direct and indirect effects of canopy cover on burn severity extremes in the west (Table 2). Future studies that specifically examine how winter energy balance beneath the forest canopy affects fuel moisture in the snow-free season will enhance our understanding of how forest structure and snowpack affect burn severity.

4.3. Within-fire variability

Because wildfires typically create a mosaic of low, moderate, and high severity burn patches, we additionally considered the effect of snow cover and forest structure on within-fire variability in burn severity. We demonstrated that, for fires greater than 500 ha, within-fire variability in burn severity increases with later SDD and longer SFD. This within-fire variability in burn severity is an important driver of landscape heterogeneity and ecosystem structure and function, as spatially heterogeneous burn areas affect the local distribution of plants and animals (Donovan et al., 2021; Turner et al., 2003). Previous studies of burn severity have generally focused on spatial patterns of high, moderate, and low severity patches at the landscape scale (Cansler and McKenzie, 2014; San-Miguel et al., 2020), which have been attributed to variations in fuel structure and abundance (Whitman et al., 2018). Snowmelt timing, in turn, has a direct influence on moisture availability and the drying of litter fuels (Harpold, 2016) and is also spatially heterogeneous. Indeed, snowmelt-driven differences in fuel moisture may contribute to the spatially complex mosaic of burn patches (Cansler and McKenzie, 2014; San-Miguel et al., 2020).

The influence of an earlier SDD on increased burn severity is concerning given recent findings that snow cover duration in the boreal forest has already decreased by 5–10 % in recent decades (Derksen et al., 2019), with particularly rapid decreases in the 1980s and early 1990s (Brown, 2000). These decreases in snow cover duration are predominately caused by earlier snowmelt in the spring (Vincent et al., 2015). In our models, a longer SFD (caused by an earlier SDD) increased burn severity extremes and within-fire variability in burn severity. As climate change continues to cause further warming, an increasingly long SFD will likely lead to more forest areas experiencing extreme burn severity. In turn, more severe and variable wildfires will have negative effects on boreal forest resilience and recovery (Turner et al., 2003; Whitman et al., 2019). To better understand how SDD affects the probability of high severity burn patches, future work should more explicitly examine how spatial patterns of SDD are correlated with spatial patterns in burn severity. This knowledge could be useful to help forest managers identify and mitigate areas that are at risk for high-severity burns.

4.4. Study limitations

One potential limitation of our study is the difference in the number of fires between ecoregions. More fires occurred in the west ($n = 613$) than in the east ($n = 76$) due to known differences in moisture and forest structure, which we expected to reduce the eastern region's sensitivity to snow dynamics. Although the lower sample size creates additional uncertainty with respect to our conclusions regarding how snow affects fire in the east, we did find evidence that burn severity was less sensitive to SDD and SFD in the east (Table 2; Figures 3, S5, and S6). Given that the eastern boreal forest (i) experiences more annual precipitation than the west (Price et al., 2013) and (ii) may be more resilient to climate change than the west (D'Orangeville et al., 2016; Couillard et al., 2021), it is possible that these eastern forests have a greater capacity to withstand the potential impacts that moisture deficits (e.g., changes in snow cover) have on burn severity.

A second limitation of our approach is that estimating snow cover from satellite imagery is challenging and imperfect. For example, snow cover can be partially obscured by the canopy in densely forested areas (Hall et al., 2002). However, the MODIS snow cover product attempts to correct for this effect by using the normalized difference vegetation index (NDVI) and normalized difference snow index (NDSI) together to estimate snow cover. Because snow cover reduces NDVI, the MODIS data classifies areas with high NDSI and low NDVI (e.g., ~0.1) as snow, thereby minimizing potential bias (Klein et al., 1998; Riggs et al., 2015). We also note that previous studies have similarly used MODIS-derived data to quantify SDD in forest ecosystems (Gleason et al., 2019). We believe our method represents the best available approach, as improving models that rely on snow cover dynamics will require future inclusion of more detailed data acquired through active remote sensing techniques such as lidar, Synthetic Aperture Radar (Sentinel), and ground-based methods.

5. Conclusion

Snow cover dynamics directly affect wildfire burn severity in seasonally snow-covered regions. These effects vary with forest structure, ecozone and ecoregion level, and how burn severity is measured. However, climate change is altering the distribution and amount of snow cover as well as the timing and rate of snowmelt, ultimately leading to increased wildfire severity. Although the consequences of climate change on snow cover have not been a major focus of wildfire research, our work highlights the importance of incorporating snow cover dynamics into future models of wildfire burn severity. Improved understanding of how snow dynamics affect burn severity will help inform resource allocation (e.g., funding, monitoring, personnel), fuel reduction, and forest management strategies to reduce the risk of high-severity wildfire and maintain forest ecosystem health and function. Future research into how snow dynamics affect burn severity remains necessary to improve our capacity to forecast the ecological consequences of wildfire in the boreal forest and to guide proactive and effective conservation and management strategies.

CRediT authorship contribution statement

Goldman Jack A: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **James Patrick M. A.:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Marie-Josée Fortin:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Funding

This work was supported by an NSERC PGS-D and OGS-QEIIGSST scholarship to J.A Goldman; NSERC Discovery Grant and CRC to M.-J. Fortin; NSERC Discovery Grant, NSERC/Canada Wildfire Strategic Network Grant and funding from the Ontario Ministry of Natural Resources and Forestry to P.M.A. James.

Declaration of Competing Interest

The authors declare that they have no financial interests or personal relationships that could have influenced the work presented in this paper.

Acknowledgments

We would like to thank Dr. Mike Wotton for comments on the methodology and assistance with the processing of the drought code. We would like to thank Dr. Bill Shipley for valuable insights and comments into the structural equation models used in the analysis. We would like to thank the Ontario Ministry of Natural Resources.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123180.

Data availability

The data is available in Zenodo and the link is: https://doi.org/10.5281/zenodo.13694676.

References

Balland, V., Bhatti, J., Errington, R., Castonguay, M., Arp, P.A., 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). Can. J. Soil Sci. 86, 203–217. https://doi.org/10.4141/S05-088.

Baltzer, J.L., Day, N.J., Walker, X.J., Greene, D., Mack, M.C., Alexander, H.D., Arseneault, D., Barnes, J., Bergeron, Y., Boucher, Y., Bourgeau-Chavez, L., Brown, C. D., Carriere, S., Howard, B.K., Gauthier, S., Parisien, M.A., Reid, K.A., Rogers, B.M., Roland, C., Sirois, L., Stehn, S., Thompson, D.K., Turetsky, M.R., Veraverbeke, S., Whitman, E., Yang, J., Johnstone, J.F., 2021. Increasing fire and the decline of fire adapted black spruce in the boreal forest. Proc. Natl. Acad. Sci. U A 118. https://doi.org/10.1073/pnas.2024872118.

Beaudoin, A., Bernier, P.Y., Villemaire, P., Guindon, L., Guo, X.J., 2017. Species composition, forest properties and land cover types across Canada's forests at 250m resolution for 2001 and 2011. https://doi.org/10.23687/EC9E2659-1C29-4DDB-87A2-6ACED147A990.

Bergeron, Y., Irulappa Pillai Vijayakumar, D.B., Ouzennou, H., Raulier, F., Leduc, A., Gauthier, S., 2017. Projections of future forest age class structure under the influence of fire and harvesting: implications for forest management in the boreal forest of eastern Canada. For.: Int. J. For. Res. 90, 485–495. https://doi.org/10.1093/forestry/cpx022.

Beverly, J.L., Martell, D.L., 2005. Characterizing extreme fire and weather events in the boreal shield ecozone of ontario. Agric. For. Meteor. 133, 5–16. https://doi.org/10.1016/j.agrformet.2005.07.015.

Brown, R.D., 2000. Northern hemisphere snow cover variability and change, 1915–97. J. Clim. 13, 2339–2355. https://doi.org/10.1175/1520-0442(2000)013<2339:NHSCVA>2.0.CO;2.

Cansler, C.A., McKenzie, D., 2014. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the Northern cascade range, USA. Ecol. Appl. 24, 1037–1056. https://doi.org/10.1890/13-1077.1.

Coops, N.C., Hermosilla, T., Wulder, M.A., White, J.C., Bolton, D.K., 2018. A thirty year, fine-scale, characterization of area burned in Canadian forests shows evidence of regionally increasing trends in the last decade. PLoS One 13, e0197218. https://doi.org/10.1371/journal.pone.0197218.

Couillard, P.-L., Payette, S., Lavoie, M., Frégeau, M., 2021. Precarious resilience of the boreal forest of eastern North America during the holocene. For. Ecol. Manag 485, 118954. https://doi.org/10.1016/j.foreco.2021.118954.

Crumley, R.L., Palomaki, R.T., Nolin, A.W., Sproles, E.A., Mar, E.J., 2020. SnowCloudMetrics: snow information for everyone. Remote Sens 12, 3341. https://doi.org/10.3390/rs12203341.

D'Orangeville, L., Duchesne, L., Houle, D., Kneeshaw, D., Cote, B., Pederson, N., 2016. Northeastern North America as a potential refugium for boreal forests in a warming climate. Science 352, 1452–1455. https://doi.org/10.1126/science.aaf4951.

Davis, R.E., Hardy, J.P., Ni, W., Woodcock, C., McKenzie, J.C., Jordan, R., Li, X., 1997. Variation of snow cover ablation in the boreal forest: a sensitivity study on the effects of conifer canopy. J. Geophys. Res. Atmospheres 102, 29389–29395. https://doi.org/10.1029/97JD01335.

Derksen, C., Burgess, D., Duguay, C., Howell, S., Murdryk, L., Smith, S., Thackeray, C., Kirchmeier-Young, M., 2019. Changes in snow, ice, and permafrost across Canada, in: Canada's changing climate report. Government of Canada, Ottawa, ontario, pp. 194–260. https://doi.org/10.4095/314614.

Dickerson-Lange, S.E., Gersonde, R.F., Hubbart, J.A., Link, T.E., Nolin, A.W., Perry, G.H., Roth, T.R., Wayand, N.E., Lundquist, J.D., 2017. Snow disappearance timing is dominated by forest effects on snow accumulation in warm winter climates of the pacific northwest, United States. Hydrol. Process 31, 1846–1862. https://doi.org/10.1002/hyp.11144.

Donovan, V.M., Dwinnell, S.P.H., Beck, J.L., Roberts, C.P., Clapp, J.G., Hiatt, G.S., Monteith, K.L., Twidwell, D., 2021. Fire-driven landscape heterogeneity shapes habitat selection of bighorn sheep. J. Mammal. 102, 757–771. https://doi.org/10.1093/jmammal/gyab035.

Douma, J.C., Shipley, B., 2021. A multigroup extension to piecewise path analysis. Ecosphere 12. https://doi.org/10.1002/ecs2.3502.

Ellis, T.M., Bowman, D.M.J.S., Jain, P., Flannigan, M.D., Williamson, G.J., 2022. Global increase in wildfire due to climate-driven declines in fuel moisture. Glob. Change Biol. 28, 1544–1559. https://doi.org/10.1111/gcb.16006.

Estes, B.L., Knapp, E.E., Skinner, C.N., Uzoh, F.C.C., 2012. Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, Northern california, USA. Int. J. Wildland Fire 21, 428–435.

Fricker, J.M., Wang, J.R., Chen, H.Y.H., Duinker, P.N., 2013. Stand age structural dynamics of conifer, mixedwood, and hardwood stands in the boreal forest of central Canada. Open J. Ecol. 03, 215. https://doi.org/10.4236/oje.2013.33025.

Gergel, D.R., Nijssen, B., Abatzoglou, J.T., Lettenmaier, D.P., Stumbaugh, M.R., 2017. Effects of climate change on snowpack and fire potential in the Western USA. Clim. Change 141, 287–299. https://doi.org/10.1007/s10584-017-1899-y.

Gleason, K.E., McConnell, J.R., Arienzo, M.M., Chellman, N., Calvin, W.M., 2019. Four-fold increase in solar forcing on snow in Western U.S. Burned forests since 1999. Nat. Commun. 10, 2026. https://doi.org/10.1038/s41467-019-09935-y.

Gottlieb, A.R., Mankin, J.S., 2024. Evidence of human influence on Northern hemisphere snow loss. Nature 625, 293–300. https://doi.org/10.1038/s41586-023-06794-y.

Guindon, L., Gauthier, S., Manka, F., Parisien, M.-A., Whitman, E., Bernier, P., Beaudoin, A., Villemaire, P., Skakun, R., 2021. Trends in wildfire burn severity across Canada, 1985 to 2015. Can. J. For. Res. 51, 1230–1244. https://doi.org/10.1139/cjfr-2020-0353.

Halim, M.A., Chen, H.Y.H., Thomas, S.C., 2019. Stand age and species composition effects on surface albedo in a mixedwood boreal forest. Biogeosciences 16, 4357–4375. https://doi.org/10.5194/bg-16-4357-2019.

Hall, D.K., Riggs, G.A., Salomonson, V.V., DiGirolamo, N.E., Bayr, K.J., 2002. MODIS snow-cover products. Remote Sens. Environ. 83, 181–194. https://doi.org/10.1016/S0034-4257(02)00095-0.

Hanes, C., Wotton, M., Woolford, D.G., Martell, D.L., Flannigan, M., 2020. Preceding fall drought conditions and overwinter precipitation effects on spring wildland fire activity in Canada. Fire 3, 24. https://doi.org/10.3390/fire3020024.

Hanes, C.C., Wang, X., Jain, P., Parisien, M.-A., Little, J.M., Flannigan, M.D., 2019. Fire-regime changes in Canada over the last half century. Can. J. For. Res. 49, 256–269. https://doi.org/10.1139/cjfr-2018-0293.

Harpold, A.A., 2016. Diverging sensitivity of soil water stress to changing snowmelt timing in the Western U.S. Adv. Water Resour. 92, 116–129. https://doi.org/10.1016/j.advwatres.2016.03.017.

Harpold, A.A., Molotch, N.P., Musselman, K.N., Bales, R.C., Kirchner, P.B., Litvak, M., Brooks, P.D., 2015. Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. Hydrol. Process 29, 2782–2798. https://doi.org/10.1002/hyp.10400.

Harvey, J.E., 2023. Battling the inferno: Canada's 2023 historic wildfire season.

Heldmyer, A., Livneh, B., Molotch, N., Rajagopalan, B., 2021. Investigating the relationship between peak Snow-Water equivalent and snow timing indices in the Western United States and Alaska. Water Resour. Res. 57, e2020WR029395. https://doi.org/10.1029/2020WR029395.

Hessilt, T.D., Rogers, B.M., Scholten, R.C., Potter, S., Janssen, T.A.J., Veraverbeke, S., 2024. Geographically divergent trends in snow disappearance timing and fire ignitions across boreal North America. Biogeosciences 21, 109–129. https://doi.org/10.5194/bg-21-109-2024.

Holsinger, L.M., Parks, S.A., Saperstein, L.B., Loehman, R.A., Whitman, E., Barnes, J., Parisien, M., Disney, M., Bohlman, S., 2021. Improved fire severity mapping in the north American boreal forest using a hybrid composite method. Remote Sens. Ecol. Conserv. https://doi.org/10.1002/rse2.238.

Jain, P., Flannigan, M.D., 2017. Comparison of methods for spatial interpolation of fire weather in alberta, Canada. Can. J. For. Res. 47, 1646–1658. https://doi.org/10.1139/cjfr-2017-0101.

Jain, P., Wang, X., Flannigan, M.D., 2017. Trend analysis of fire season length and extreme fire weather in North America between 1979 and 2015. Int. J. Wildland Fire 26, 1009. https://doi.org/10.1071/WF17008.

Jain, P., Barber, Q.E., Taylor, S.W., Whitman, E., Castellanos Acuna, D., Boulanger, Y., Chavardès, R.D., Chen, J., Englefield, P., Flannigan, M., Girardin, M.P., Hanes, C.C., Little, J., Morrison, K., Skakun, R.S., Thompson, D.K., Wang, X., Parisien, M.-A., 2024. Drivers and impacts of the Record-Breaking 2023 wildfire season in Canada. Nat. Commun. 15, 6764. https://doi.org/10.1038/s41467-024-51154-7.

James, P.M., Robert, L.E., Wotton, B.M., Martell, D.L., Fleming, R.A., 2017. Lagged cumulative spruce budworm defoliation affects the risk of fire ignition in ontario, Canada. Ecol. Appl. 27, 532–544. https://doi.org/10.1002/eap.1463.

Kane, V.R., Cansler, C.A., Povak, N.A., Kane, J.T., McGaughey, R.J., Lutz, J.A., Churchill, D.J., North, M.P., 2015. Mixed severity fire effects within the rim fire: relative importance of local climate, fire weather, topography, and forest structure. For. Ecol. Manag 358, 62–79. https://doi.org/10.1016/j.foreco.2015.09.001.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116–126. https://doi.org/10.1071/WF07049.

Key, C.H., Benson, N.C., 2006. Landscape Assessment: Ground Measure of Severity, the Composite Burn Index; and Remote Sensity of Severity, the Normalized Burn Ratio. (Gen. Tech. Rep), FIREMON: Fire Effects Monitoring and Inventory System. Ogden, UT.

Klein, A.G., Hall, D.K., Riggs, G.A., 1998. Improving snow cover mapping in forests through the use of a canopy reflectance model. Hydrol. Process 12, 1723–1744. https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1723::AID-HYP691>3.0.CO;2-2.

Lefcheck, J.S., 2016. piecewiseSEM: piecewise structural equation modelling in r for ecology, evolution, and systematics. Methods Ecol. Evol. 7, 573–579. https://doi.org/10.1111/2041-210x.12512.

Lundquist, J.D., Dickerson-Lange, S.E., Lutz, J.A., Cristea, N.C., 2013. Lower forest density enhances snow retention in regions with warmer winters: a global framework developed from plot-scale observations and modeling. Water Resour. Res. 49, 6356–6370. https://doi.org/10.1002/wrcr.20504.

Mudryk, L.R., Derksen, C., Howell, S., Laliberté, F., Thackeray, C., Sospedra-Alfonso, R., Vionnet, V., Kushner, P.J., Brown, R., 2018. Canadian snow and sea ice: historical trends and projections. Cryosphere 12, 1157–1176. https://doi.org/10.5194/tc-12-1157-2018.

Natural Resources Canada. 2024. High Resolution Digital Elevation Model (HRDEM) - CanElevation Series. Open Government Portal. ⟨https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995⟩.

Ontario Ministry of Natural Resources and Forestry, 2021. Fire Disturbance Area.

Parisien, M., Barber, Q.E., Flannigan, M.D., Jain, P., 2023. Broadleaf tree phenology and springtime wildfire occurrence in boreal Canada. Glob. Change Biol., gcb.16820 https://doi.org/10.1111/gcb.16820.

Parks, S.A., Dillon, G.K., Miller, C.A., 2014a. A new metric for quantifying burn severity: the relativized burn ratio. Remote Sens 6, 1827–1844. https://doi.org/10.3390/rs6031827.

Parks, S.A., Miller, C., Nelson, C.R., Holden, Z.A., 2014b. Previous fires moderate burn severity of subsequent wildland fires in two large Western US wilderness areas. Ecosystems 17, 29–42. https://doi.org/10.1007/s10021-013-9704-x.

Parks, S.A., Holsinger, L.M., Panunto, M.H., Jolly, W.M., Dobrowski, S.Z., Dillon, G.K., 2018. High-severity fire: evaluating its key drivers and mapping its probability across Western US forests. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aab791.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., authors, E., Heisterkamp, S., Van Willigen, B., Ranke, J., R Core Team, 2023. nlme: Linear and Nonlinear Mixed Effects Models.

Pomeroy, J.W., Gray, D.M., Hedstrom, N.R., Janowicz, J.R., 2002. Prediction of seasonal snow accumulation in cold climate forests. Hydrol. Process 16, 3543–3558. https://doi.org/10.1002/hyp.1228.

Price, D.T., Alfaro, R.I., Brown, K.J., Flannigan, M.D., Fleming, R.A., Hogg, E.H., Girardin, M.P., Lakusta, T., Johnston, M., McKenney, D.W., Pedlar, J.H., Stratton, T., Sturrock, R.N., Thompson, I.D., Trofymow, J.A., Venier, L.A., 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ. Rev. 21, 322–365. https://doi.org/10.1139/er-2013-0042.

R Core Team, 2023. R: A language and environment for statistical computing.

Riggs, G.A., Hall, D.K., Roman, M.O., 2015. VIIRS Snow Cover Algorithm Theoretical Basis Document (ATBD).

Riley, S., Degloria, S., Elliot, S.D., 1999. A terrain ruggedness index that quantifies topographic heterogeneity. Int. J. Sci. 5, 23–27.

Rogers, B.M., Soja, A.J., Goulden, M.L., Randerson, J.T., 2015. Influence of tree species on continental differences in boreal fires and climate feedbacks. Nat. Geosci. 8, 228–234. https://doi.org/10.1038/ngeo2352.

Roth, T.R., Nolin, A.W., 2017. Forest impacts on snow accumulation and ablation across an elevation gradient in a temperate montane environment. Hydrol. Earth Syst. Sci. 21, 5427–5442. https://doi.org/10.5194/hess-21-5427-2017.

Ryan, K., 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fenn. 36. https://doi.org/10.14214/sf.548.

San-Miguel, I., Coops, N.C., Chavardès, R.D., Andison, D.W., Pickell, P.D., 2020. What controls fire spatial patterns? Predictability of fire characteristics in the Canadian boreal plains ecozone. Ecosphere 11. https://doi.org/10.1002/ecs2.2985.

Shipley, B., 2016. Cause and Correlation in Biology: A User's Guide to Path Analysis, Structural Equations and Causal Inference with R, 2nd ed. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139979573.

Shipley, B., Douma, J.C., 2020. Generalized AIC and chi-squared statistics for path models consistent with directed acyclic graphs. Ecology 101. https://doi.org/10.1002/ecy.2960.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., Skinner, W.R., 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. 108. https://doi.org/10.1029/2001jd000484.

Talucci, A.C., Krawchuk, M.A., 2019. Dead forests burning: the influence of beetle outbreaks on fire severity and legacy structure in sub-boreal forests. Ecosphere 10, e02744. https://doi.org/10.1002/ecs2.2744.

Talucci, A.C., Meigs, G.W., Knudby, A., Krawchuk, M.A., 2022. Fire severity and the legacy of mountain pine beetle outbreak: high-severity fire peaks with mixed live and dead vegetation. Environ. Res. Lett. 17, 124010. https://doi.org/10.1088/1748-9326/aca2c1.

Taylor, A.H., Poulos, H.M., Kluber, J., Issacs, R., Pawlikowski, N., Barton, A.M., 2021. Controls on spatial patterns of wildfire severity and early post-fire vegetation development in an arizona sky island, USA. Landsc. Ecol. 36, 2637–2656. https://doi.org/10.1007/s10980-021-01260-4.

Turner, J.A., Canada, CanadaE., Service, C.F., 1972. The drought code component of the Canadian forest fire behavior system. Canadian forestry service publication. Department of the Environment.

Turner, M.G., Romme, W.H., Tinker, D.B., 2003. Surprises and lessons from the 1988 Yellowstone fires. Front. Ecol. Environ. 1, 351–358. https://doi.org/10.1890/1540-9295(2003)001[0351:SALFTY]2.0.CO;2.

Van Wagner, C.E., 1987. Development and structure of the Canadian forest fire weather index system, forestry technical report. Minister of Supply and Services Canada, Ottawa.

Varhola, A., Coops, N.C., Weiler, M., Moore, R.D., 2010. Forest canopy effects on snow accumulation and ablation: an integrative review of empirical results. J. Hydrol. 392, 219–233. https://doi.org/10.1016/j.jhydrol.2010.08.009.

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, E., Milewska, E.J., Wan, H., Wang, X.L., 2015. Observed trends in Canada's climate and influence of Low-Frequency variability modes. J. Clim. 28, 4545–4560. https://doi.org/10.1175/JCLI-D-14-00697.1.

Wang, Y., 2024. The effect of climate change on forest fire danger and severity in the Canadian boreal forests for the period 1976–2100. J. Geophys. Res. Atmospheres 129, e2023JD039118. https://doi.org/10.1029/2023JD039118.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase Western U.S. Forest wildfire activity. Science 313, 940–943. https://doi.org/10.1126/science.1128834.

Whitman, E., Parisien, M.-A., Thompson, D.K., Hall, R.J., Skakun, R.S., Flannigan, M.D., 2018. Variability and drivers of burn severity in the northwestern Canadian boreal forest. Ecosphere 9. https://doi.org/10.1002/ecs2.2128.

Whitman, E., Parisien, M.A., Thompson, D.K., Flannigan, M.D., 2019. Short-interval wildfire and drought overwhelm boreal forest resilience. Sci. Rep. 9, 18796. https://doi.org/10.1038/s41598-019-55036-7.

Whitman, E., Parisien, M.-A., Holsinger, L.M., Park, J., Parks, S.A., 2020. A method for creating a burn severity Atlas: an example from alberta, Canada. Int. J. Wildland Fire 29. https://doi.org/10.1071/wf19177.

Whitman, E., Parks, S.A., Holsinger, L.M., Parisien, M.-A., 2022. Climate-induced fire regime amplification in alberta, Canada. Environ. Res. Lett. 17. https://doi.org/10.1088/1748-9326/ac60d6.

Wotton, B.M., Flannigan, M.D., Marshall, G.A., 2017. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. Environ. Res. Lett. 12, 095003. https://doi.org/10.1088/1748-9326/aa7e6e.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x.