Received: 19 October 2023 | Revised: 14 January 2024 | Accepted: 22 January 2024

DOI: 10.1111/gcb.17221

Global Change Biology WILEY

RESEARCH ARTICLE

Mapping the distance between fire hazard and disaster for communities in Canadian forests

Xianli Wang[1] | Tom Swystun[2] | Colin B. McFayden[2] | Sandy Erni[2] | Jacqueline Oliver[1,3] | Stephen W. Taylor[4] | Mike D. Flannigan[3]

[1]Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, Edmonton, Alberta, Canada

[2]Great Lakes Forestry Centre, Canadian Forest Service, Natural Resources Canada, Sault Ste. Marie, Ontario, Canada

[3]Natural Resource Science, Thompson Rivers University, Kamloops, British Columbia, Canada

[4]Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada, Victoria, British Columbia, Canada

Correspondence
Xianli Wang, Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada, 5320-122nd Street Northwest, Edmonton, AB T6H 3S5, Canada.
Email: xianli.wang@nrcan-rncan.gc.ca

Funding information

Canadian Safety and Security Program, Grant/Award Number: CSSP-2016-CP-2286 and CSSP-2018-TI-2406

Abstract

Communities interspersed throughout the Canadian wildland are threatened by fires that have become bigger and more frequent in some parts of the country in recent decades. Identifying the fireshed (source area) and pathways from which wildland fire may ignite and spread from the landscape to a community is crucial for risk-reduction strategy and planning. We used outputs from a fire simulation model, including fire polygons and rate of spread, to map firesheds, fire pathways and corridors and spread distances for 1980 communities in the forested areas of Canada. We found fireshed sizes are larger in the north, where the mean distances between ecumene and fireshed perimeters were greater than 10 km. The Rayleigh *Z* test indicated that simulated fires around a large proportion of communities show significant directional trends, and these trends are stronger in the Boreal Plains and Shields than in the Rocky Mountain area. The average distance from which fire, when spreading at the maximum simulated rate, could reach the community perimeter was approximately 5, 12 and 18 km in 1, 2 and 3 days, respectively. The average daily spread distances increased latitudinally, from south to north. Spread distances were the shortest in the Pacific Maritime, Atlantic Maritime and Boreal Plains Ecozones, implying lower rates of spread compared to the rest of the country. The fire corridors generated from random ignitions and from ignitions predicted from local fire history differ, indicating that factors other than fuel (e.g. fire weather, ignition pattern) play a significant role in determining the direction that fires burn into a community.

KEYWORDS
Canada, fire corridor, fire risk, fireshed, rate of spread, simulation modelling

1 | INTRODUCTION

Canada has experienced more intense wildland fire seasons over the last decades, with the occurrence of more frequent uncontrollable large wildland fires (Coogan et al., 2020; Hanes et al., 2019). Wildland fires are expected to continue to increase in burned area (e.g. Boulanger et al., 2018; Wang et al., 2020, 2022), frequency (Wang et al., 2022; Wotton et al., 2010) and intensity (Wotton et al., 2017) in

Xianli Wang and Tom Swystun contributed equally to this paper.

the coming decades under changing climate conditions (e.g. Coogan et al., 2020; Hanes et al., 2019; Whitman et al., 2022). Wildland fires can cause a range of losses and disruptions with attendant health, safety, social, economic and cultural impacts (Johnston et al., 2020; McFayden et al., 2019), including reduced air quality (Matz et al., 2020) and extensive evacuations (e.g. Yellowknife 2023, Kelowna 2003 and 2023, Fort McMurray 2016). When a wildland fire enters a community, the results can be devastating. Recent examples of such devastation include the 2023 fire that destroyed 151 homes (Halifax Examiner, 2023, https://www.halifaxexaminer.ca/environment/fires/halifax-considers-shrinking-evacuation-area-reports-151-homes-lost-in-tantallon-fire/) in Tantallon, a suburb of Halifax, Nova Scotia, as well as the 2023 McDougall Creek fire that burned an estimated 189 structures in and around the communities of West Kelowna and Kelowna, British Columbia (CBC, 2023, https://www.cbc.ca/news/canada/british-columbia/mcdougall-creek-wildfire-no-held-1.6975199). The current and continuing expansion of industrial and urban development into wildland areas will intensify the challenge for wildland fire managers and those who are responsible for community safety. The capacity for fire suppression will likely not keep pace with increasing fire activity (e.g. Podur & Wotton, 2010; Wang et al., 2022), while fire protection costs (i.e. mitigation, fire preparedness, response and recovery costs) will continue to rise (Stocks & Martell, 2016).

The Canadian Wildland Fire Strategy, established in 2004 and renewed in 2016 (CCFM, 2016), identified a critical need to enhance wildland fire prevention and mitigation capability. One major effort is to promote FireSmart® (https://firesmartcanada.ca/resources/) concepts (e.g. the seven principles, including education, emergency planning, vegetation management, legislation, development, interagency cooperation and cross-training [https://firesmartcanada.ca/about-firesmart/the-seven-firesmart-disciplines/]) to all wildland fire-affected regions across Canada. Reducing wildland fire risk will require collaboration between wildland fire risk managers and stakeholders that is a whole-of-society approach, and building knowledge and tools to support FireSmart risk reduction (CCFM, 2021; CIFFC, 2022, https://ciffc.ca/sites/default/files/2022-02/PM_Action_Plan_Public_2022_02_01.pdf). Here, wildland fire risk is defined as the interaction between fire hazard (likelihood and intensity) and vulnerability (e.g. Erni et al., 2023) or between likelihood and impacts (e.g. Johnston et al., 2020; McFayden et al., 2019). Although much of the wildland fire mitigation effort in Canada to date has been focussed on household, neighbourhood and community-level scales (e.g. FireSmart@), wildland fire risk reduction at a regional/landscape scale has also been promoted (Acuna et al., 2010; CIFFC, 2022; Hirsch et al., 2001). Identifying the fireshed (source area) and pathways from which fire can spread from the landscape to a community is crucial for risk-reduction strategy and planning.

Landscape wildland fire risk reduction planning needs to be done weeks, months or years before a fire event. During this process, it is important to determine the source area and fastest pathways from which fire can spread from the landscape to a community or other valued asset, in addition to the potential fire spread distances and directions. The source area, or fireshed, is the area around a community from which a fire could ignite and spread to that community or other asset of interest. A fireshed is similar in concept to a watershed but is probabilistic rather than deterministic. The source area of land that drains into a particular body of water is a fixed set of all upslope points that can contribute flow, whereas the source area of fires impacting a community is influenced both by fixed (e.g. topography, fuels) and stochastic (e.g. weather and ignition) factors. A fire pathway, on the other hand, is the route connecting an ignition location (source) in a fireshed to a point on a community ecumene boundary (sink).

While fuel connection is crucial to provide a pathway for wildland fire to spread to a community (e.g. Beverly & Forbes, 2023), fire spread distance and direction are also influenced by weather and topography. In this study, we investigate how fire spread rates and fire perimeters generated from fire simulation models can be used to map firesheds, fire pathways and spread distances. The Canadian Fire Behavior Prediction (FBP) System (FCFDG, 1992) is used to predict fire behaviour (e.g. rate of spread [ROS], direction and intensity) based on fuel, weather and topography. It is applied within the fire growth simulation model Prometheus (Tymstra et al., 2010), to account for heterogeneous fuels and topography and varying fire weather over the simulation time period and spatial domain.

The probabilistic landscape fire simulation model Burn P3 (Parisien et al., 2005) uses Prometheus to grow fires from ignition points based on fuels, topography and fire-conducive weather conditions observed in the landscape domain. Annual fire occurrence, spread event days and daily fire weather distributions are used to emulate stochastic aspects of physical fire processes and the fire environment (Parisien et al., 2005 and references therein for more detail). The model repeatedly simulates annual fire ignitions, growth and final perimeters of a large number (tens of thousands) of times to exhaust all the possible ways fires could ignite and spread through the landscape (e.g. Parisien et al., 2013). The simulated fire polygons (perimeter extents) are used to estimate burn probability and fire behaviour statistics, such as mean and maximum fire intensity, ROS and fuel consumption (FCFDG, 1992; Hirsch, 1996; Wotton et al., 2009) at each location (i.e. raster pixel). BurnP3 has been used in several landscape studies in Canada (e.g. Parisien et al., 2007, 2011, 2013, 2019; Wang et al., 2016), and has been extended to the national scale (Erni et al., 2023).

In the subsequent sections of this paper, we provide methodologies and information to support the planning of fuel management activities to reduce wildland fire spread to communities. Using the national Burn P3 outputs (Erni et al., 2023), we develop novel methods to (1) delineate the fireshed for each community within the forested areas of Canada; (2) estimate the general direction(s) from which wildland fires are most likely to ignite and spread into the community by Canadian Ecozone; (3) assess the time for wildland fire to reach the community from any location; and (4) map fire pathways by which wildland fires may enter the community.

2 | METHODS

2.1 | Study area

Our study area is predominantly the forested areas of Canada, which are bounded by the shrub tundra in the north, and the extensively cultivated and developed urban areas in the south. Topographically, the Western Cordillera system rises in the west, and the rest of the country is relatively flat. Three major biomes, the temperate coniferous (west coast), the temperate broadleaf and mixed (east coast and Great Lakes area) and the boreal (central Canada and north of the other two biomes), constitute the main body of Canadian forests. The analysis included a total of 1980 communities within the Canadian forests. Communities of interest were limited to those with populations ≥200, based on 2016 Canadian Census Populations (Statistics Canada, 2017), as many communities with a population <200 were found to be temporary (or abandoned) settlements (Parisien et al., 2020). In this study, the Canadian Ecozones (ESWG, 1996; Figure 1a) were used as the primary analysis units.

2.2 | Data used in the analysis

2.2.1 | National fire simulation outputs

Outputs of the Burn P3 simulation model for Canadian forests (Erni et al., 2023) were used in this study. Specifically, we used the 250-m resolution grid-based FBP System variable ROS, the simulated fire perimeters (GIS polygons) and the ignition location of the simulated fire perimeters (coordinates).

In the simulation, ignition locations were selected based on the ignition grids, which are rasterized maps of relative ignition probability (i.e. the probability of an ignition occurring in any pixel can only be measured by comparing it to the probability of ignition in any other pixel). Historical fire ignitions (≥50 ha and after 1969) from the Canadian National Fire Database were used in the creation of these grids, which are based on independent variables including elevation (m), solar radiation (Wh/m^2), topographic position index, road density (km/km^2) and distance to development (km). Here, development includes any urban, built-up area or railway. Daily weather (local noon temperature, relative humidity, wind speed and direction and 24-h precipitation) and associated components from the Fire Weather Index (FWI) System (Van Wagner, 1987) were used to simulate fire spread. Because Burn-P3 exclusively models days in which fires achieve appreciable spread (e.g. Parisien et al., 2005, 2013), we retained days having high or extreme fire weather conditions, as defined by a FWI ≥19 (Podur & Wotton, 2010). A sequential list of fire weather days (FWI ≥19) was used in fire growth simulation for a specific fire, and the duration of fire burning was determined by a random draw from the historical fire burning duration distribution (for more details, please see Erni et al., 2023).

2.2.2 | Community boundaries

Data representing community boundaries were extracted from the Canadian Ecumene Database Version 2.0 (CanEcumene; Eddy et al., 2020a), which was derived from remote sensing of night-light imagery. The CanEcumene maps communities across Canada based on natural boundaries that capture the populated areas more accurately than the solely administrative boundaries found in census data (Eddy et al., 2020b). In addition, for illustrative purposes, the urban and built-up land cover class was extracted from the North American Land Cover Monitoring System (NALCMS) at 30 m-resolution for the year 2015 (http://www.cec.org/north-american-land-change-monitoring-system/), using the ecumene area of each community as the mask.

Urban areas were set to non-fuel for the fire simulations, as is a common practice in Burn P3 modelling (e.g. Parisien et al., 2013;

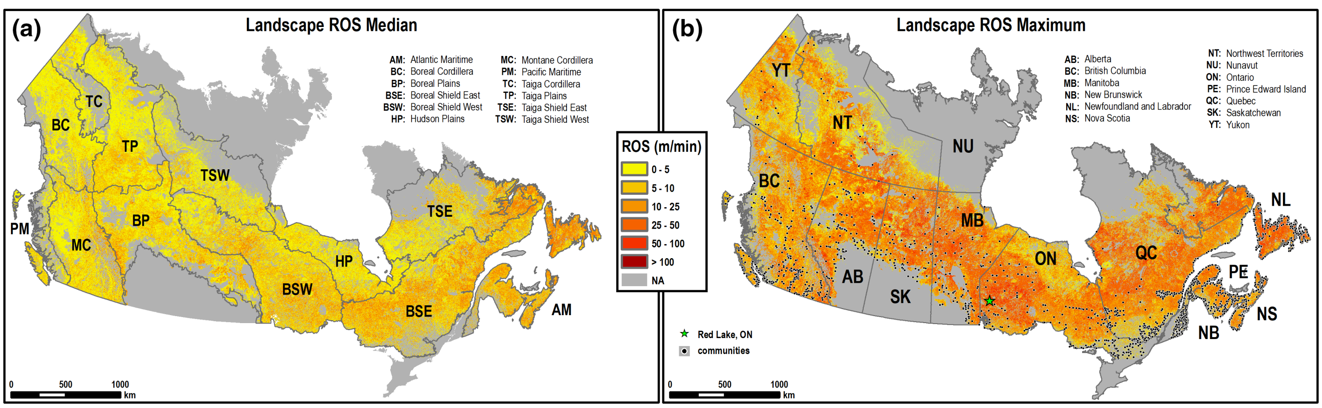


FIGURE 1 Median and maximum ROS. (a) Median ROS for each 250 m-resolution pixel, with Canadian Ecozones (ESWG, 1996) overlaid. The Southern Arctic and Mixed Wood Plains were excluded from the study as they were not included in the BP3 modelling of forested areas (Erni et al., 2023). (b) Maximum ROS for each 250 m-resolution pixel. Included communities are shown as black points. Red Lake, ON, is highlighted as a green star; it was selected as the example community to present the methodologies applied in this study. Canadian Provinces and Territories are overlaid for orientation. Prince Edward Island was excluded from this study as it was not included in the BP3 modelling of forested areas (Erni et al., 2023). ROS, rate of spread.

Wang et al., 2016); this means simulated fires never intersect the urban and built-up area.

2.3 | Mapping fire spread isochrons and fire pathways for individual communities

Most of our analyses are conducted within the fireshed, the boundary of which is delineated by the union of all simulated fire polygons that intersect with the ecumene area of a community.

2.3.1 | Delineating fire spread isochrons to communities

Burn P3 generates a distribution of ROS values for each pixel in the landscape based on the number of simulated fires affecting that pixel. Median and maximum ROS were computed for each pixel, resulting in median and maximum ROS raster layers. It's important to note that real-world ROS may vary for any actual fire in space–time (Erni et al., 2023). The median ROS represents the general trend, while the maximum ROS is more meaningful for fire management, as extreme events are of greater concern.

We used the accumulated cost surface function `accCost` (Dijkstra, 1959) from the `gdistance` package (Van Etten, 2017) in R (R Core Team., 2023) to calculate the time (minutes) it would take for fire to spread from each pixel within the community fireshed, through the shortest path, to the community's ecumene edge using inverted ROS (m/min inverted to min/m) as the cost value. ROS was inverted because the shortest time distance was the desired output, and the `accCost` function calculates the lowest cost path (i.e. the inversion of higher ROS values equates to lower time values; Figure 2a and 2c). From the output raster surface layer of the `accCost` function, contours were generated to show the time for fire to spread across the landscape to the community ecumene in 2-h intervals (Figure 2b and 2d). In this study, both median and maximum ROS were used to generate fire spread contours.

2.3.2 | Mapping the simulated fire pathways and corridors

A fire pathway is the fastest route (measured in minutes) by which fire may spread from an ignition location (source) to the nearest point on a community ecumene boundary (sink) (e.g. Figure 2a); it is not necessarily the shortest route in terms of distance. A fire corridor, on the other hand, is a common channel shared by fire pathways that converge towards the same sink. Fire corridors highlight preferential routes by which fires may spread towards a community. Because ignition potential and fire spread rates and directions vary at daily and seasonal scales with vegetation phenology and moisture, synoptic weather conditions and atmospheric stability (among other factors), fireshed boundaries and pathway locations may also vary within and between years. Our simulations attempt to incorporate time by varying ignition density, weather stream values, leaf-out dates and foliar moisture trends within the fire regime analysis units. Thus, we estimate the long-term expected fireshed boundary and pathway locations based on an approximately 40-year data record (see also Erni et al., 2023).

We used the accumulated cost surface function (`shortestPath`) from the `gdistance` package in R to calculate the fastest path from the ignition location of each fireshed fire to the nearest point of intersection between the fireshed fire perimeter and the community ecumene. The pathway was constrained to stay within the perimeter of the fireshed fire with the ROS (median or maximum) as the underlying cost layer that guides the pathway (Figure 3a–c). This method was used for all fires that ignited within the fireshed but outside of the community ecumene. By using the same median or maximum ROS raster to guide the fastest pathway direction, the fire pathways often converged. These fire pathways were then dissolved into a single feature: the fire corridors. The corridors were split into segments, with each segment representing a unique line between junctions and/or end points. The density of fire pathways that traverse each corridor segment was calculated and expressed as a percentage based on all pathways. We found the resulting fire pathways/corridors to be very similar in form, regardless of which ROS was used as the cost layer.

2.3.3 | Mapping seeded fire pathways and corridors

Fireshed fire ignitions tend to cluster close to the community because of human activity. As a result, the fire behaviours captured by fire corridors are based on the limited relevant historical fire samples. To map fire corridors for all possible fires without considering spatial distributions, we randomly seeded the fireshed with hypothetical ignition locations spaced approximately 1 km apart. With the fireshed boundary constraining the fire pathway routes, the seeded fire pathways and corridors for the same community were mapped using the method described in the previous section.

2.4 | Analysis

2.4.1 | Fire spread directional trends

Determining if fires are likely to spread to a community from one or more predominant directions can provide important information for coarse and quick identification of concerning fires, or to highlight areas for fuel treatment. We calculated the mean directional angle of the fireshed fire ignitions (i.e. ignition locations of fires that intersected the community ecumene) in relation to community ecumene centroids and tested its significance using the Rayleigh *Z* test (Jammalamadaka & SenGupta, 2001). We calculated the angular dispersion for *n* directional samples (each with an Azimuth of θ_i) to see if

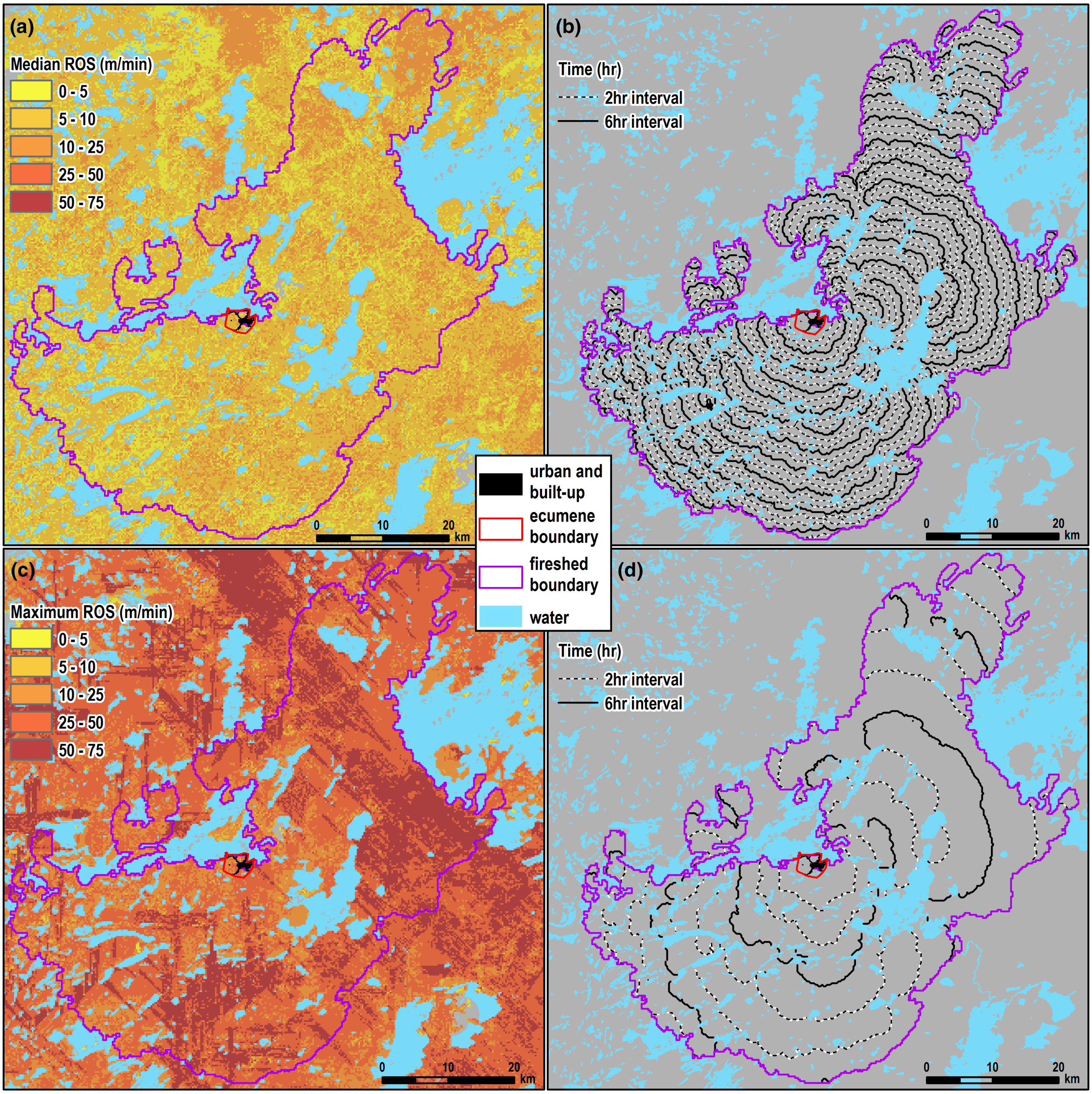


FIGURE 2 Fireshed, landscape ROS (median/maximum) and contour maps of time for fires to reach the ecumene boundary of Red Lake, ON. (a) Median ROS layer. The red line shows the ecumene boundary. The black polygon shows North American Land Cover Monitoring System (NALCMS) urban and built-up areas within the ecumene. The purple line shows the fireshed boundary. (b) Contour map of time for fire to reach the ecumene boundary based on the median ROS. Black/white dashed lines show 2-h interval contours for fire within the fireshed to spread to the ecumene boundary using the median ROS as the cost layer. Solid black lines highlight 6-h intervals. (c) Maximum ROS layer. (d) Contour map of time for fire to reach the ecumene boundary based on maximum ROS. ROS, rate of spread.

it is closer to a uniform or concentrated dispersion (Jammalamadaka & SenGupta, 2001): $r = \sqrt{x^2 + y^2}$, where $x = \left(\sum_{i=1}^{n} \sin\theta_i\right) / n$, $y = \left(\sum_{i=1}^{n} \cos\theta_i\right) / n$, while $r=0$ indicates a completely uniform dispersion and $r=1$ shows a complete concentration in one direction. Using these parameters, we calculated the mean direction of approaching fire around each community (i.e. $\cos\overline{\theta} = x / r$, $\sin\overline{\theta} = y / r$), where the mean direction in degrees would be: $\omega_r = \arctan\left(\sin\overline{\theta} / \cos\overline{\theta}\right)$. We then used the R function `rayleigh.test` in the `circular` package (Agostinelli & Lund, 2017) for the Rayleigh Z test (significance level $\alpha = .05$), where $Z = nr^2$. A significant Rayleigh Z test indicates a true directional fire approach; alternatively, there is no clear directional fire approaches to the community. The estimates for each community were summarized by Ecozone to show the spatial variations of directional fire approaches.

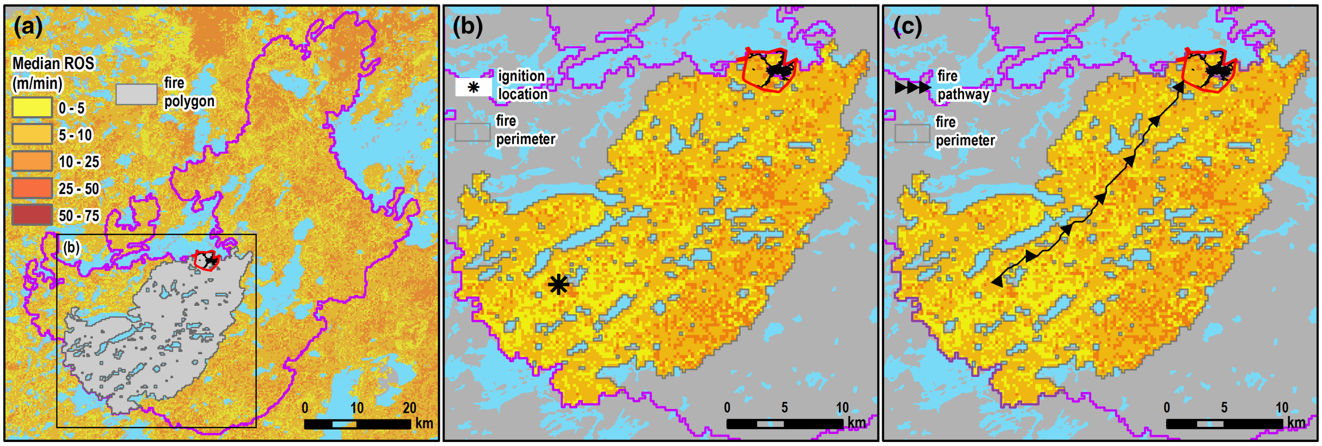


FIGURE 3 Generating the fire pathway of a simulated fire for Red Lake, ON. (a) An example of a fire polygon in grey. The red line shows the ecumene boundary. The black polygon shows North American Land Cover Monitoring System (NALCMS) urban and built-up areas within the ecumene. The purple line shows the fireshed boundary. Background is the median ROS. (b) The median ROS layer within the example fire polygon. A black asterisk shows the ignition location of an example fire. (c) Fastest distance fire pathway from the ignition location to the nearest location of the ecumene boundary. The fire pathway is constrained within the fire perimeter. ROS, rate of spread.

2.4.2 | Spread distances of fires reaching communities

Three distance measures were determined for all communities, representing the distance from which a fire could spread to the community in 1, 2 and 3 days using maximum and median ROS, respectively (Figure 4). Transects emanating from the ecumene centroid were drawn every 5°. Distance was measured along each transect from the ecumene edge to median/maximum 1–3-day spread isochrons, where hours of burning/day matched Burn P3 modelling (Erni et al., 2023). The average and standard deviation were calculated from valid distance measures for each community, and for each of the three daily distances. Because seasonality of ROS values was not part of our Burn P3 outputs (Erni et al., 2023), these distances were only measured for the entire fire season.

The three daily distances' metrics were later summarized by Ecozone. We calculated the coefficient of variation (CV) for each community, where a larger CV indicates a stronger directional tendency for fires that intersect the community ecumene.

2.4.3 | Comparison of fire corridors generated by fireshed fires and seeded fires

We compared the seeded fire pathways and corridors with those derived from the fireshed fires (simulated ignitions). The more disparate the two, the stronger the indication that fire activity within the area is influenced by a variety of fire-conducive conditions, including fuel distribution, topographic constraints, ignition patterns and fire weather (e.g. wind direction). Similarity between the two implies that fuel distribution is the predominant factor in shaping fireshed pathways and corridors (see also Beverly & Forbes, 2023).

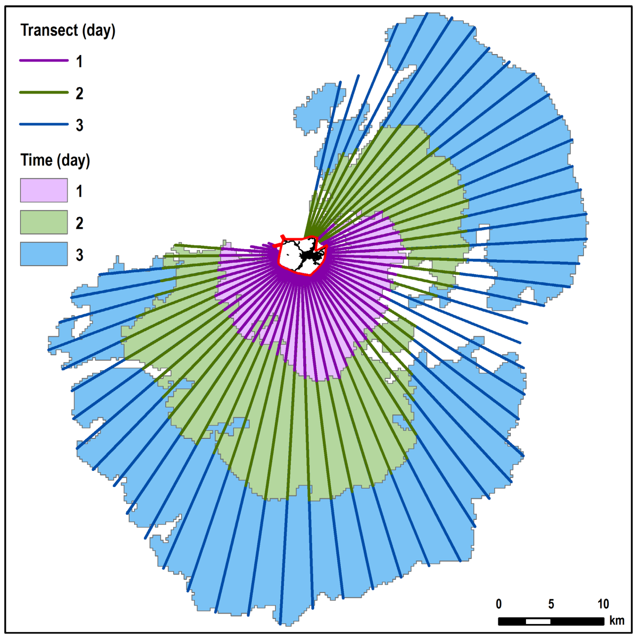


FIGURE 4 Mapping distances of fires 1–3 days away from the Red Lake, ON, ecumene. The red line shows the ecumene boundary. The black polygon shows North American Land Cover Monitoring System (NALCMS) urban and built-up areas within the ecumene.

3 | RESULTS

3.1 | Fireshed characteristics by Ecozone

Although most communities in the study are in southern Ecozones (Atlantic Maritime [AM], Boreal Shield East [BSE], Boreal Plains [BP], Montane Cordillera [MC] and Pacific Maritime [PM]), the sizes of the firesheds around communities located in the northern Ecozones (e.g. Taiga Shield West [TSW], Taiga Cordillera [TC], Hudson Plains [HP], Boreal Cordillera [BC], Taiga Plains [TP] and Taiga Shield East [TSE]) tend to be larger. The mean distance between the ecumene boundary and fireshed perimeter for communities within these northern Ecozones were all found to be much greater than 10km (Table 1; Figure 1). Boreal Shield West (BSW) extends from south to north (Figure 1), but firesheds within it showed similar features to those in the northern Ecozones.

3.2 | Fire spread directional trends

For a substantial proportion of communities within each Ecozone, the Rayleigh *Z* test indicated that fires approach from a predominant direction, particularly for those in the boreal and taiga plains and shields (Figure 1; Table 2). However, the directional strength varies among the different zones (e.g. Table 3). Ecozones in mountainous regions (e.g. BC and MC) showed weaker directional trends, while the taiga shields (TSE and TSW) were among the strongest. As illustrated in Figure 5, the direction of fire pathways and corridors had a central tendency within Ecozones that is likely associated with the primary wind direction on spread event days in the historical weather data. Over the entire study area, the spread direction of fires reaching communities showed a significant directional trend for 71.5% of the communities when both lightning and human-caused fires were grouped together. More specifically, 47.8% of communities showed a significant directional trend for lightning-caused fires and 68.8% of communities for human-caused fires.

3.3 | Spread distances of fires reaching communities

The fire spread distances reaching the subject communities at a fixed time interval (hours) are not uniform; this can be seen in the bi-hourly contour map (Figure 2d). Summarized by Ecozone and using maximum ROS, we found the shortest 1–3-day spread distances (i.e. slower spread) for fire to reach communities were in the PM, followed by AM and BP Ecoregions (Table 4; Figure 1). These distances ranged from 1.7 and 3.25km for fires 1-day away, 3.69 and 7.17km for fires 2-days away and 5.91 and 11.86km for fires 3-days away. The rest have differences that are not statistically significant: averaging about 5.91km (ranging between 5.13 and 6.76km) for fire perimeters 1-day away from the communities, 13.52km (between 11.59 and 17.97km) for fires 2-days away and 20.65km (between 17.16 and 28.46km) for fires 3-days away. Across the country, the average 1-, 2- and 3-day spread distances are 5.07, 11.55 and 17.79km, respectively. The same pattern was found when fires grew at median speeds (Table S1), where across the country, they averaged 1-, 2- and 3-day distances are 1.42, 2.99 and 4.56km. There are no significant differences for coefficient of variation values among the Ecozones considered (Table 4; Table S1).

3.4 | Comparison of fire corridors generated by fireshed fires and seeded fires

Fire pathways and corridors created based on fireshed fires (Burn P3 model output) may overlap those generated by seeded fires (Figure 6b,c vs. Figure 6e,f). This is expected, as the fireshed fires (Figure 6a) should be a subset of the seeded fires (Figure 6d) if their number is large enough to represent all fire pathways and corridors. However, fire pathways and corridors created based on fireshed fires showed comparatively more spatial variation in most of the communities considered. For example, in Red Lake, ON, simulated fires burning into the community from the northeast (Figure 6b,c) are much less frequent in comparison to the potential (Figure 6e,f), and more fires from the southwest may burn into the community than those from

TABLE 1 The size and number of firesheds as well as the distance between ecumene and fireshed edge by Ecozone.

	Fireshed size (km^2)						Distance to perimeter (km)
Ecozone	PCT25	PCT50	PCT75	Max	Mean (SD)	Number	Mean (SD)
AM	6	20	40	812	33 (59)	612	1.6 (1.1)
BC	392	1076	2434	8296	1723 (2023)	16	18.1 (11.6)
BP	13	160	1038	24,494	1379 (3176)	197	11.1 (15.1)
BSE	33	343	872	8375	607 (899)	619	9.4 (8.4)
BSW	485	1394	2617	11,210	1937 (2054)	115	19.3 (12.2)
HP	516	696	1283	2706	966 (806)	10	16.7 (10.8)
MC	156	318	505	3429	404 (429)	204	8.3 (4.4)
PM	8	13	26	1872	40 (149)	166	1.5 (1.6)
TC	2106	2106	2106	2106	2106 (NA)	1	23.6 (NA*)
TP	684	1388	2261	21,345	3834 (5850)	18	20.4 (15.8)
TSE	126	771	7903	14,646	3607 (4941)	12	23.1 (24.8)
TSW	2168	3003	4907	7765	3391 (2285)	10	20.6 (13.1)

Abbreviations: AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; HP, Hudson Plains; MC, Montane Cordillera; PCT25, 25th percentile; PCT50, 50th percentile (median); PCT75, 75th percentile; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TSE, Taiga Shield East; TSW, Taiga Shield West. *NA: not applicable.

TABLE 2 Proportion of communities with a significant fire spread directional trend by Ecozone.

EZ	A	L	H
AM	0.66	0.33	0.65
BC	0.94	0.75	0.50
BP	0.77	0.60	0.76
BSE	0.70	0.39	0.68
BSW	0.84	0.68	0.81
HP	1.00	0.90	1.00
MC	0.69	0.39	0.62
PM	0.76	0.49	0.73
TP	0.88	0.82	0.73
TSE	0.92	0.67	0.91
TSW	1.00	1.00	0.89

Note: TC is not shown because only one community in TC.

Abbreviations: A, all fires together; AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; H, human-caused fires; HP, Hudson Plains; L, lightning fires; MC, Montane Cordillera; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TSE, Taiga Shield East; TSW, Taiga Shield West.

TABLE 3 Fire spread direction angular dispersion (*r*) values for communities with significant trend by Ecozone.

EZ	A	L	H
AM	0.52 (0.21)	0.67 (0.18)	0.52 (0.22)
BC	0.32 (0.11)	0.34 (0.14)	0.41 (0.16)
BP	0.52 (0.24)	0.60 (0.23)	0.53 (0.24)
BSE	0.54 (0.18)	0.77 (0.16)	0.54 (0.18)
BSW	0.49 (0.20)	0.55 (0.19)	0.50 (0.18)
HP	0.58 (0.22)	0.63 (0.21)	0.57 (0.23)
MC	0.36 (0.17)	0.55 (0.20)	0.36 (0.17)
PM	0.56 (0.22)	0.61 (0.22)	0.56 (0.22)
TP	0.48 (0.23)	0.50 (0.22)	0.50 (0.22)
TSE	0.66 (0.17)	0.69 (0.12)	0.72 (0.16)
TSW	0.66 (0.21)	0.67 (0.20)	0.70 (0.13)

Note: TC is not shown because only one community in TC.

Abbreviations: A, all fires together; AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; H, human-caused fires; HP, Hudson Plains; L, lightning fires; MC, Montane Cordillera; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TSE, Taiga Shield East; TSW, Taiga Shield West.

other directions, although fuel connectivity is not the limiting factor, as shown in the seeded fire pathways and corridors. The spatial distribution of fire ignitions is therefore shown to determine the directions of simulated fires burning into an individual community.

4 | DISCUSSION

More than 90% of fires that occur near communities in Canada are suppressed at a small size during the initial attack. However, uncontrolled fires spreading from nearby locations under extreme burning conditions will challenge suppression and increase the chance of disaster. In this study, we introduced novel methods to map firesheds, fire pathways and fire corridors for 1980 communities within the forested area of Canada. We also mapped the bi-hourly fire front contours around each of these communities based on the ROS values outputted from the Burn P3 models. By summarizing the 1–3-day fire spread distances, we found that daily spread was typically faster in northern areas than in southern and coastal regions. We suspect fuel composition, fragmentation, longer active burning hours and fire management may all influence this trend. We also found that for a substantial proportion of communities, fires are more likely to approach from certain directions and that these directional trends are more pronounced in the boreal shield and plains than in the mountain areas.

Fire frequency, distribution and growth are influenced by various factors, including weather, topography, fuel and ignition patterns (e.g. Flannigan et al., 2009; Stocks et al., 1989). Because these factors are generally not randomly distributed, it is unlikely that fires would occur and spread randomly around a specific community. Our finding that fires are more likely to approach communities from certain directions is not surprising. Accordingly, the question is not whether these directional trends should exist, but rather, how strong are these directional trends. Communities with strong directional trends in simulation reflect trends of fire-conducive environmental factors, especially fire weather conditions (e.g. wind direction), fuel distribution (Beverly & Forbes, 2023) and ignition patterns. On the other hand, topography potentially modifies the spatial trends of these factors, which may weaken the directional trends for some communities while strengthening them for others. We suspect that fire directions in the plains or shield are more likely to be affected by general atmospheric circulation patterns (e.g. Westerly NW/SW), while topographic features (direction, shape and altitude of the mountains and valleys) are more likely to influence wind directions and fire spread directions in mountainous areas. However, further research is needed to disentangle the complicated interactions among these factors and how they affect the directions in which fires may spread.

By converging fire pathways into fire corridors, the main routes by which fires may spread into the communities were identified. In combination with the fire progressing contour map, both the spread direction and distance (median and extreme scenarios) of fires to the community could be assessed. Impacts of recent burns and land cover (e.g. water bodies) are also clearly reflected in the pathways, which implies that, as with other factors related to fuel distribution, these pathways are variable through time. For example, the disturbance of fuels by recent fires that have burned just north of the community of La Ronge, Saskatchewan (Figure S1) has meant that very few of the modelled fire corridors approach the community from the north, even though this has historically been the most 'high-risk' area and the anticipated direction for approaching fires, according to a local expert (personal communication). However, this would be reflected in future updated fire corridors when these disturbed fuels

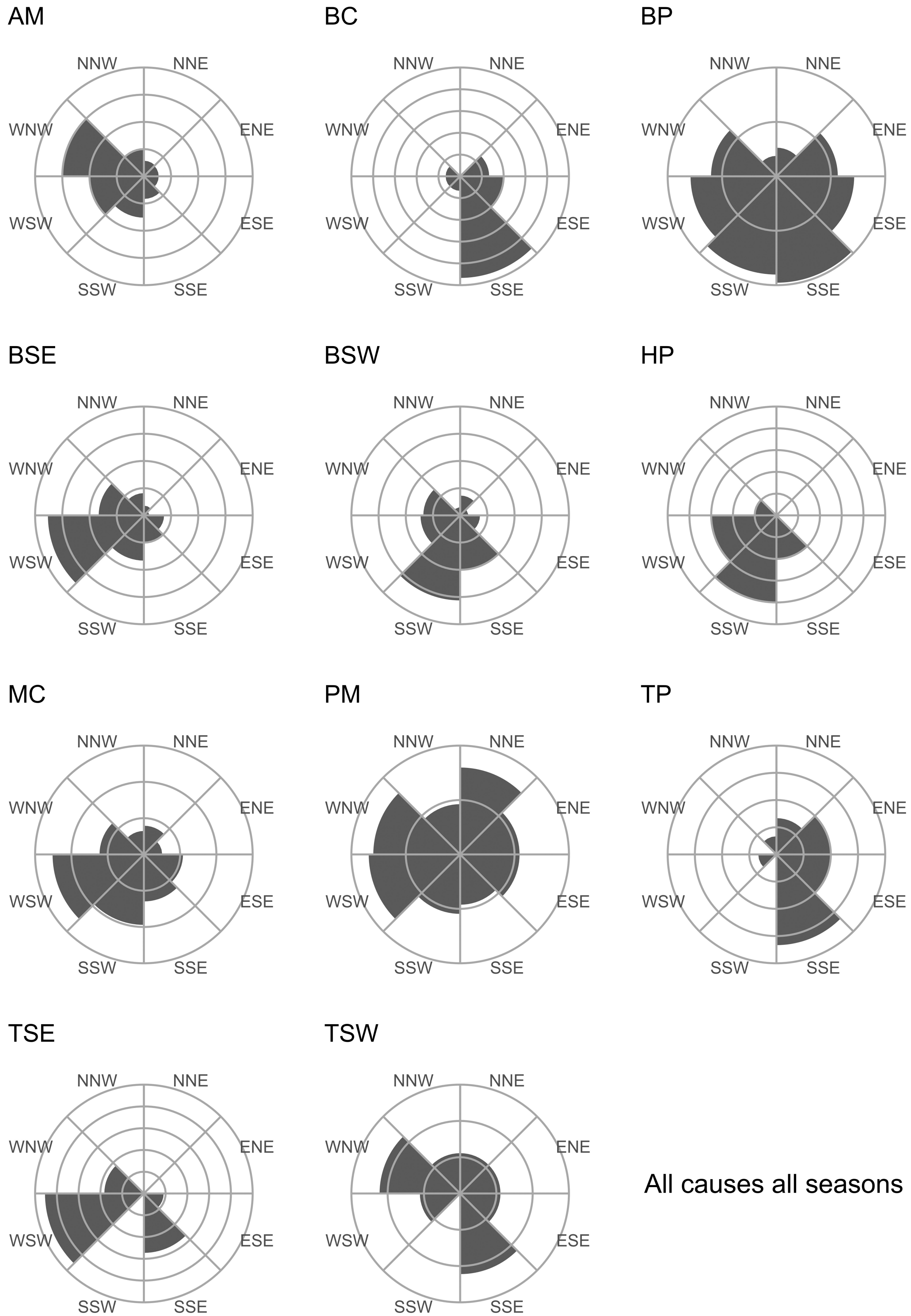


FIGURE 5 Fire spread directions (%) by Ecozone (see also Figure 1 for their full names) with all causes and seasons together. The shaded area represents the percentage of communities with significant directional fire approach by eight secondary intercardinal directions. Within each plot, a circle represents a 10% increment from the centre out.

are restored to maturity. In addition, differences between fire corridors created by the two mapping approaches (i.e. based on fireshed fires and seeded fire ignitions) may vary by community. Factors such as ignition agents and fire weather conditions may play a larger role when there are greater differences between the results of the two approaches.

Although it is well known that prevention—education, industrial regulation (e.g. Granville et al., 2022), fire bans and forest closures—may effectively reduce human-caused fires (e.g. Tymstra et al., 2020), there is still much to be gained from the information provided from this study. Staff from two Canadian fire management agencies that are working on strategies for fire mitigation suggested the results of this study may be informative in both strategic fire management planning and risk assessments for individual communities. In addition, the 2023 fire season in Canada demonstrated the value and usefulness of this study, as some of the fires threatening the Canadian communities matched the fire corridors we generated (e.g. Figure S2 for the fires close to Yellowknife in August of 2023). With more accurate fire hazard assessment inputs (e.g. fire weather, fuel distribution and improved fire spread models), the mapped corridors would more accurately capture how extreme fires might enter a community, which would be critical information for landscape-scale FireSmart planning (CIFFC, 2022). Clearly, a constellation of models (e.g. fire hazard/risk assessment model (Parisien et al., 2005), fire damage assessment model (Abo El Ezz et al., 2022) and fire corridors created in this study) are crucial to inform real-world decisions. Our intent is not to provide the sole solution to assessing risk for a community, but to provide information to support decision-makers.

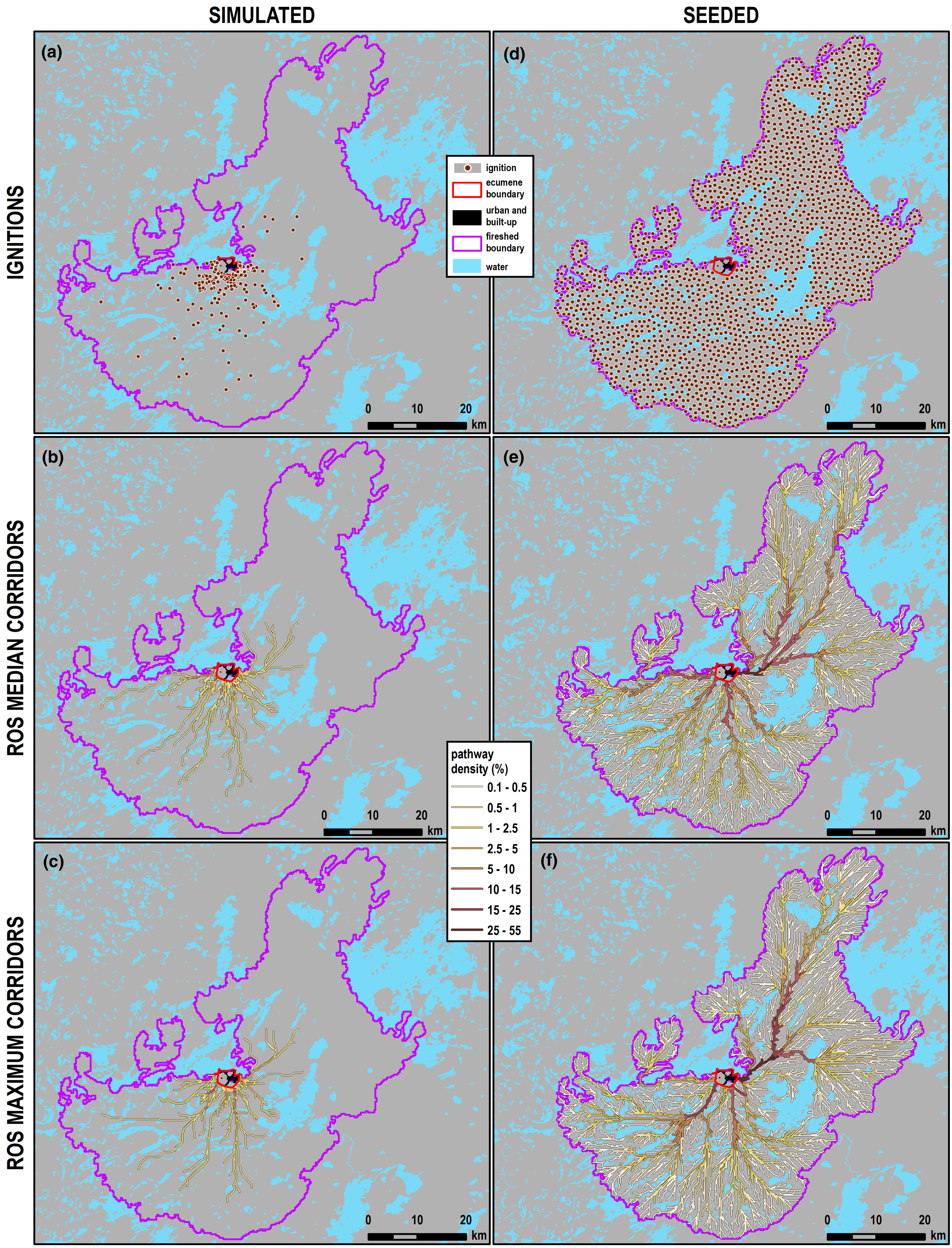
To use modelling for real-world decision-making, decision-makers must be aware of what a model does and does not account for. Any modelling exercise is bound by constraints and limitations, and our study is no exception. Some common limitations to this approach to modelling are that reliable spatial fire records for this study area are only available since 1980 (e.g. Hanes et al., 2019), and associated key parameters (e.g. ROS) are not available due to the difficulty in retaining relevant historical weather and fuel conditions. Due to these limitations, the direction and distance of past fires that have approached communities can often only be assessed by simulation modelling. Other limitations are inherent in the modelling inputs (e.g. Parisien et al., 2013), and the algorithms used in fire growth modelling (e.g. FCFDG, 1992; Hirsch, 1996; Tymstra et al., 2010; Van Wagner, 1987; Wotton et al., 2009). Future scenarios may not be represented, as important weather and fuel factors are expected to change relative to the historical norm (e.g. Stralberg et al., 2018; Wang et al., 2015), and climate change was not accounted for by the Burn P3 scenarios used in this study. Although suppression efforts are indirectly represented by using the fire size distribution in Burn P3 model calibrations (Erni et al., 2023; Parisien et al., 2013), any change in future fire management capacity or performance will not be accurately reflected in this study. Importantly,

TABLE 4 Mean distance (standard deviation; km) of fire fronts (*d*) to ecumene at 1–3 days based on the maximum rate of spread (ROS) by Ecozone accompanied by the mean coefficient of variation (CV) (standard deviation) over all communities within the Ecozone.

	Day 1		Day 2		Day 3	
Ecozone	*d*	CV	*d*	CV	*d*	CV
AM	2.69 (1.40)	0.35 (0.14)	6.03 (2.78)	0.25 (0.10)	9.83 (4.07)	0.22 (0.09)
BC	5.88 (3.07)	0.29 (0.11)	12.4 (6.46)	0.27 (0.11)	18.7 (9.28)	0.25 (0.10)
BP	3.25 (2.57)	0.39 (0.17)	7.17 (5.39)	0.29 (0.13)	11.86 (8.22)	0.27 (0.13)
BSE	5.13 (3.17)	0.39 (0.20)	12.23 (6.69)	0.24 (0.11)	19.47 (9.67)	0.20 (0.10)
BSW	5.40 (2.65)	0.37 (0.20)	12.1 (5.15)	0.25 (0.11)	18.72 (7.42)	0.22 (0.10)
HP	6.56 (3.58)	0.42 (0.35)	14.8 (6.81)	0.22 (0.10)	21.40 (10.36)	0.28 (0.20)
MC	5.22 (2.07)	0.36 (0.15)	11.59 (3.86)	0.28 (0.12)	18.11 (5.42)	0.24 (0.10)
PM	1.70 (0.90)	0.39 (0.15)	3.69 (1.82)	0.30 (0.12)	5.91 (2.80)	0.26 (0.12)
TC	6.29 (NA)	0.25 (NA)	12.2 (NA)	0.24 (NA)	17.16 (NA)	0.27 (NA)
TP	5.95 (3.23)	0.37 (0.24)	12.82 (6.50)	0.28 (0.18)	19.62 (9.68)	0.28 (0.22)
TSE	5.98 (4.17)	0.50 (0.16)	15.57 (10.64)	0.30 (0.03)	24.18 (15.94)	0.27 (0.07)
TSW	6.76 (2.98)	0.49 (0.15)	17.97 (3.64)	0.29 (0.10)	28.46 (4.25)	0.25 (0.10)

Abbreviations: AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; HP, Hudson Plains; MC, Montane Cordillera; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TSE, Taiga Shield East; TSW, Taiga Shield West.

FIGURE 6 Fireshed level simulated and seeded corridors for Red Lake, ON. (a) The locations of simulated fireshed fire ignitions. (b) All fireshed fire pathways aggregated to fire corridors using median ROS as the underlying cost layer for pathway creation. (c) All fireshed fire pathways aggregated to fire corridors using maximum ROS as the underlying cost layer for pathway creation. (d) Locations of randomly seeded imitation ignitions at ~1 km spacing across the fireshed. (e) All seeded pathways aggregated to seeded corridors using median ROS as the underlying cost layer for pathway creation. (f) All seeded pathways aggregated to seeded corridors using maximum ROS as the underlying cost layer for pathway creation. ROS, rate of spread.


SIMULATED
SEEDED
IGNITIONS
ROS MEDIAN CORRIDORS
ROS MAXIMUM CORRIDORS
(a)
(b)
(c)
(d)
(e)
(f)
ignition
ecumene boundary
urban and built-up
fireshed boundary
water
pathway density (%)
0.1 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 15
15 - 25
25 - 55
0 10 20 km

spot fire propagation is not included (e.g. Parisien et al., 2005), which may overrepresent the effect of fuel continuity because fires can jump natural breaks such as lakes or rivers over longer distances. However, it is also important to consider that this approach is not prescribing mitigation decisions but rather providing insight to experts who will consider these results alongside other information to plan risk-reduction activities.

Future work should focus on improving the fire growth and burn probability approaches for individual communities. Such improvements could be achieved via more accurate input variables (e.g. fires of all sizes, local weather station records, a more accurate fuel layer), finer resolution and improved fire behaviour prediction models (e.g. the inclusion of spot fires). Further extensions simulating different mitigation options (e.g. Finney, 2004) could provide more detailed information to agencies looking to maximize the impacts of limited mitigation funds used across large landscapes.

5 | CONCLUSION

We present a method of using Burn P3 model outputs to map fireshed, fire spread isochrons, fire pathways and fire corridors for 1980 communities in the forested areas of Canada. We found that the average distance between the fire front and the point where the fire reached a community perimeter in 1, 2 and 3 days was approximately 5, 12 and 18 km, respectively. The average daily spread distances were lowest in the Pacific Maritime, Atlantic Maritime and Boreal Plains ecozones, implying lower rates of spread compared to the rest of the country. These distances increased from south to north. We found that fires that entered a large proportion of communities showed significant directional trends, and the strength of these trends is stronger in the Boreal Plains and Shield than in the Western Cordillera.

AUTHOR CONTRIBUTIONS

Xianli Wang: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Tom Swystun:** Data curation; formal analysis; investigation; methodology; software; visualization; writing – review and editing. **Colin B. McFayden:** Validation; writing – review and editing. **Sandy Erni:** Investigation; writing – review and editing. **Jacqueline Oliver:** Data curation; writing – review and editing. **Stephen W. Taylor:** Writing – review and editing. **Mike D. Flannigan:** Supervision; writing – review and editing.

ACKNOWLEDGEMENTS

We would like to acknowledge the advice from Den Boychuk from the Ontario Ministry of Natural Resources and Forestry. We thank Chris Dallyn, Dan Johnston, Josh Johnston, Maurice Lecours, Darren McLarty and Aaron Stacey for feedback and advice on the model application. We also thank Kendriah Pearse from the University of Toronto for sharing literatures that are critical to this paper, Kathryn Levesque from the Canadian Forest Service for proofreading and Wankui Zhou for editing support. This research was funded by two Canadian Safety and Security Program grants to X.W. (CSSP-2016-CP-2286 and CSSP-2018-TI-2406).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest and no competing interests.

DATA AVAILABILITY STATEMENT

A subset of the simulation data (Erni et al., 2023) used in this study as well as the primary and processed data for each of the 1,980 communities generated by this research are available from Zenodo: https://doi.org/10.5281/zenodo.10594234. All other datasets used in this study are available in the following public repositories: Community boundaries (http://www.cec.org/north-american-land-change-monitoring-system/), CanEcumene (Eddy et al., 2020a) (https://open.canada.ca/data/en/dataset/3f599fcb-8d77-4dbb-8b1e-d3f27f932a4b).

ORCID

Xianli Wang https://orcid.org/0000-0001-9873-9767

REFERENCES

Abo El Ezz, A., Boucher, J., Cotton-Gagnon, A., & Godbout, A. (2022). Framework for spatial incident-level wildfire risk modelling to residential structures at the wildland urban interface. *Fire Safety Journal*, *131*, 103625. https://doi.org/10.1016/j.firesaf.2022.103625

Acuna, M. A., Palma, C. D., Cui, W., Martell, D. L., & Weintraub, A. (2010). Integrated spatial fire and forest management planning. *Canadian Journal of Forest Research*, *40*(12), 2370–2383.

Agostinelli, C., & Lund, U. (2017). *R package 'circular': Circular statistics* (version 0.4-93). https://r-forge.r-project.org/projects/circular/

Beverly, J. L., & Forbes, A. M. (2023). Assessing directional vulnerability to wildfire. *Natural Hazards*, *117*, 831–849.

Boulanger, Y., Parisien, M.-A., & Wang, X. (2018). Model-specification uncertainty in future area burned by wildfires in Canada. *International Journal of Wildland Fire*, *27*(3), 164–175.

Canadian Council of Forest Ministers Wildland Fire Management Working Group Action Plan 2021–2026 (CCFM). (2021). *A roadmap for implementing the Canadian wildland fire strategy using a whole-of-government approach*. Fo79-25/2021E-PDF – Government of Canada Publications – Canada.ca

Canadian Wildland Fire Strategy (CCFM). (2016). *A 10-year review and renewed call to action*. Canadian Council of Forest Ministers, Ottawa, Ontario. 15 p. Fo79-22/2016E-PDF. Government of Canada Publications – Canada.ca

Coogan, S. C. P., Cai, X., Jain, P., & Flannigan, M. D. (2020). Seasonality and trends in human- and lightning-caused wildfires ≥2 ha in Canada, 1959–2018. *International Journal of Wildland Fire*, *29*(6), 473–485.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, *1*, 269–271.

Ecological Stratification Working Group (ESWG). (1996). *A national ecological framework for Canada*. Agriculture and Agri-Food Canada and Environment Canada.

Eddy, B., Muggridge, M., LeBlanc, R., Osmond, J., Kean, C., & Boyd, E. (2020a). An ecological approach for mapping socio-economic data in support of ecosystems analysis: Examples in mapping Canada's forest ecumene. *One Ecosystem*, *5*, e55881. https://doi.org/10.3897/oneeco.5.e55881

Eddy, B. G., Muggridge, M., LeBlanc, R., Osmond, J., Kean, C., & Boyd, E. (2020b). *The CanEcumene 2.0 GIS database*. Federal Geospatial Platform (FGP) [Data file]. Natural Resources Canada. https://open.canada.ca/data/en/dataset/3f599fcb-8d77-4dbb-8b1e-d3f27f932a4b

Erni, S., Wang, X., Swystun, T., Taylor, S. W., Parisien, M.-A., Robinne, F. N., Eddy, B., Oliver, J., Armitage, B., & Flannigan, M. D. (2023). Mapping wildfire risk to Canadian communities. *International Journal of Disaster Risk Reduction*, *101*, 104221. https://doi.org/10.1016/j.ijdrr.2023.104221

Finney, M. A. (2004). *Landscape fire simulation and fuel treatment optimization. Methods for integrating modeling of landscape change: Interior northwest landscape analysis system*. General Technical Report PNW-GTR-610. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, pp. 117–131.

Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M., & Gowman, L. M. (2009). Implications of changing climate for global wildland fire. *International Journal of Wildland Fire*, *18*, 483.

Forestry Canada Fire Danger Group (FCFDG). (1992). *Development and structure of the Canadian forest Fire Behavior Prediction System*. Forestry Canada, Ottawa, Information Report ST-X-3. 63 p.

Granville, K., Woolford, D. G., Dean, C. B., & McFayden, C. B. (2022). Wildland fire prevention: The impact of the Modifying Industrial Operations Protocol on the growth of industrial forestry-caused wildland fires in Ontario, Canada. *International Journal of Wildland Fire*, *31*(9), 825–834.

Hanes, C., Wang, X., Jain, P., Parisien, M.-A., Little, J., & Flannigan, M. D. (2019). Fire regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, *49*(3), 256–259.

Hirsch, K., Kafka, V., Tymstra, C., McAlpine, R., Hawkes, B., Stegehuis, H., Quintilio, S., Gauthier, S., & Peck, K. (2001). Fire-smart forest management: A pragmatic approach to sustainable forest management in fire-dominated ecosystems. *The Forestry Chronicle*, *77*(2), 357–363.

Hirsch, K. G. (1996). *Canadian forest Fire Behavior Prediction (FBP) system: user's guide*. Natural Resources Canada, Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, AB, Canada. Special Report 7. 122 p.

Jammalamadaka, S. R., & SenGupta, A. (2001). *Topics in circular statistics, sections 3.3.2 and 3.4.1*. World Scientific Press.

Johnston, L. M., Wang, X., Erni, S., Taylor, S. W., McFayden, C. B., Oliver, J. A., Stockdale, C., Christianson, A., Boulanger, Y., Gauthier, S., Arseneault, D., Wotton, B. M., Parisien, M.-A., & Flannigan, M. D. (2020). Wildland fire risk research in Canada. *Environmental Reviews*, *28*(2), 164–186.

Matz, C. J., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., Henderson, S. B., & Stieb, D. M. (2020). Health impact analysis of $PM_{2.5}$ from wildfire smoke in Canada (2013–2015, 2017–2018). *Science of the Total Environment*, *725*, 138506.

McFayden, C. B., Boychuk, D., Woolford, D. G., Wheatley, M. J., & Johnston, L. M. (2019). Impacts of wildland fire effects on resources and assets through expert elicitation to support fire response decisions. *International Journal of Wildland Fire*, *28*(11), 885–900. https://doi.org/10.1071/WF18189

Parisien, M. A., Barber, Q. E., Hirsch, K. G., Stockdale, C. A., Erni, S., Wang, X., Arseneault, D., & Parks, S. A. (2020). Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nature Communications*, *11*, 2121.

Parisien, M.-A., Dawe, D. A., Miller, C., Stockdale, C. A., & Armitage, O. B. (2019). Applications of simulation-based burn probability modelling: A review. *International Journal of Wildland Fire*, *28*, 913–926. https://doi.org/10.1071/WF19069

Parisien, M.-A., Junor, D. R., & Kafka, V. G. (2007). Comparing landscape-based decision rules for placement of fuel treatments in the boreal mixedwood of western Canada. *International Journal of Wildland Fire*, *16*, 664–672.

Parisien, M. A., Kafka, V. G., Hirsch, K. G., Todd, J. B., Lavoie, S. G., & Maczek, P. D. (2005). *Mapping wildfire susceptibility with the Burn-P3 simulation model*. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, NOR-X-405, Edmonton, AB, Canada.

Parisien, M.-A., Parks, S., Miller, C., Krawchuk, M., Heathcott, M., & Moritz, M. (2011). Contributions of ignitions, fuels, and weather to the spatial patterns of burn probability of a boreal landscape. *Ecosystems*, *14*, 1141–1155. https://doi.org/10.1007/S10021-011-9474-2

Parisien, M.-A., Walker, G., Little, J., Simpson, B., Wang, X., & Perrakis, D. (2013). Considerations for modeling burn probability across landscapes with steep environmental gradients: An example from the Columbia Mountains, Canada. *Natural Hazards*, *66*, 439–462.

Podur, J., & Wotton, M. (2010). Will climate change overwhelm fire management capacity? *Ecological Modelling*, *221*(9), 1301–1309.

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Statistics Canada. (2017). *Dictionary, census of population, 2016*. Catalogue no. 98-301-X. Ottawa, ON, Canada.

Stocks, B. J., Lawson, B. D., Alexander, M. E., Van Wagner, C. E., McAlpine, R. S., Lynham, T. J., & Dube, D. E. (1989). Canadian forest fire danger rating system: An overview. *The Forestry Chronicle*, *65*, 258–265. https://doi.org/10.5558/tfc65258-4

Stocks, B. J., & Martell, D. L. (2016). Forest fire management expenditures in Canada: 1970–2013. *The Forestry Chronicle*, *92*, 298–306.

Stralberg, D., Wang, X., Parisien, M.-A., Robinne, F. N., Sólymos, P., Mahon, C. L., Nielsen, S. E., & Bayne, E. M. (2018). Wildfire-mediated vegetation change in boreal forests of Alberta, Canada. *Ecosphere*, *9*(3), e02156.

Tymstra, C., Bryce, R. W., Wotton, B. M., Taylor, S. W., & Armitage, O. B. (2010). *Development and structure of Prometheus: The Canadian wildland fire growth simulation model*. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre Information Report NOR-X-417, Edmonton, AB, Canada.

Tymstra, C., Stocks, B. J., Cai, X., & Flannigan, M. D. (2020). Wildfire management in Canada: Review, challenges and opportunities. *Progress in Disaster Science*, *5*, 100045.

Van Etten, J. (2017). R package gdistance: Distances and routes on geographical grids. *Journal of Statistical Software*, *76*(1), 1–21. https://doi.org/10.18637/jss.v076.i13

Van Wagner, C. E. (1987). *Development and structure of the Canadian forest fire weather index system*. Forest Technology Report 35. Canadian Forestry Service.

Wang, X., Parisien, M.-A., Taylor, S., Perrakis, D., Little, J., & Flannigan, M. (2016). Future burn probability in south-central British Columbia. *International Journal of Wildland Fire*, *25*, 200–212.

Wang, X., Studens, K., Parisien, M.-A., Taylor, S. W., Candau, J.-N., Boulanger, Y., & Flannigan, M. D. (2020). Projected changes in fire size from daily spread potential in Canada over the 21st century. *Environmental Research Letters*, *15*(10), 104048.

Wang, X., Swystun, T., & Flannigan, M. D. (2022). Future wildfire extent and frequency determined by the longest fire-conducive weather spell. *Science of the Total Environment*, *830*, 154752. https://doi.org/10.1016/j.scitotenv.2022.154752

Wang, X., Thompson, D., Marshall, G. A., Tymstra, C., Carr, R., & Flannigan, M. D. (2015). Increasing frequency of extreme fire weather in Canada with climate change. *Climatic Change*, *130*(4), 573–586. https://doi.org/10.1007/s10584-015-1375-5

Whitman, E., Parks, S., Holsinger, L., & Parisien, M.-A. (2022). Climate-induced fire regime amplification in Alberta, Canada. *Environmental Research Letters*, *17*, 055003. https://doi.org/10.1088/1748-9326/ac60d6

Wotton, B. M., Alexander, M. E., & Taylor, S. W. (2009). *Updates and revisions to the 1992 Canadian forest Fire Behavior Prediction system*. Natural Resources Canada, Canadian Forestry Service, Great Lakes Forestry Center, Sault Ste. Marie, Ontario, Canada. Information Report GLC-X-10, 45 p.

Wotton, B. M., Flannigan, M. D., & Marshall, G. A. (2017). Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters*, *12*(9), 095003.

Wotton, B. M., Nock, C. A., & Flannigan, M. D. (2010). Forest fire occurrence and climate change in Canada. *International Journal of Wildland Fire*, *19*(3), 253–271. https://doi.org/10.1071/WF09002

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Wang, X., Swystun, T., McFayden, C. B., Erni, S., Oliver, J., Taylor, S. W., & Flannigan, M. D. (2024). Mapping the distance between fire hazard and disaster for communities in Canadian forests. *Global Change Biology*, *30*, e17221. https://doi.org/10.1111/gcb.17221