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ARTICLE

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Short- and long-term wildfire threat when adapting infrastructure for wildlife conservation in the boreal forest

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Abstract

Managers designing infrastructure in fire-prone wildland areas require assessments of wildfire threat to quantify uncertainty due to future vegetation and climatic conditions. In this study, we combine wildfire simulation and forest landscape composition modeling to identify areas that would be highly susceptible to wildfire around a proposed conservation corridor in Québec, Canada. In this measure, managers have proposed raising the conductors of a new 735-kV hydroelectric powerline above the forest canopy within a wildlife connectivity corridor to mitigate the impacts to threatened boreal woodland caribou (*Rangifer tarandus*). Retention of coniferous vegetation, however, can increase the likelihood of an intense wildfire damaging powerline infrastructure. To assess the likelihood of high-intensity wildfires for the next 100 years, we evaluated three time periods (2020, 2070, 2120), three climate scenarios (observed, RCP 4.5, RCP 8.5), and four vegetation projections (static, no harvest, extensive harvesting, harvesting excluded in protected areas). Under present-day conditions, we found a lower probability of high-intensity wildfire within the corridor than in other parts of the study area, due to the protective influence of a nearby, poorly regenerated burned area. Wildfire probability will increase into the future, with strong, weather-induced inflation in the number of annual ignitions and wildfire spread potential. However, a conversion to less-flammable vegetation triggered by interactions between climate change and disturbance may attenuate this trend. By addressing the range of uncertainty of future conditions, we present a robust strategy to assist in decision-making about long-term risk management for both the proposed conservation measure and the powerline.

KEYWORDS
burn probability, climate change, mitigation management, powerlines, wildfire threat assessment, wildland fire, wildlife connectivity

INTRODUCTION

The wildland–human interface (WHI), which is the area where wilderness and human features including housing, infrastructure, and industry overlap (Robinne et al., 2016), is growing across North America (Johnston & Flannigan, 2017; Theobald & Romme, 2007). As the WHI expands, the intermingling of human development and forested vegetation has resulted in wildland fire becoming a growing threat to human values (Erni et al., 2021). In the boreal forests of Canada, wildfire is the dominant disturbance factor (Stocks et al., 2003), affecting on average nearly 3 million hectares per year over the last decade (Hanes et al., 2019). Despite substantial provincial and federal investments in wildfire agencies across Canada, several catastrophic fires in the WHI have occurred in recent decades (Hope et al., 2016; Stocks & Martell, 2016). The interaction of wildfire with public infrastructure, such as power grids, can have particularly disruptive outcomes, causing widespread power outages that affect public health and economic productivity (Campbell & Lowry, 2012; Klinger et al., 2014). Given these possible severe impacts, managers designing infrastructure in fire-prone areas require a means of assessing wildfire threat that spans the projected lifetime of infrastructure projects.

Changing climate is expected to have complex, interactive feedbacks with disturbance, complicating any long-term assessment of wildfire threat. Climate conditions are anticipated to become more conducive to wildfire occurrence (Flannigan, Krawchuk, et al., 2009) and spread (Wang et al., 2017), leading to more frequent years of substantial wildfire activity (Boulanger et al., 2013). In eastern Canada, forests have been extensively managed for decades, with clearcut harvesting altering vegetation patterns across the landscape (Boucher et al., 2009). Given that changing climatic conditions often favor deciduous species at the expense of the typical, highly flammable coniferous species of the boreal forest (Boulanger & Pascual Puigdevall, 2021), disturbances such as wildfire or clearcut harvesting can act as a catalyst for widespread vegetation composition shifts (Brice et al., 2020; Danneyrolles et al., 2019; Stralberg et al., 2018). Such changes in boreal forest composition would have a significant dampening effect on wildfire activity that may counteract more suitable climatic conditions for fire activity (Krawchuk & Cumming, 2011; Terrier et al., 2013).

Any understanding of future wildfire regimes, and the corresponding changes to wildfire hazard, must therefore include the interplay between changing climate, vegetation, disturbance, and forest management. However, assessing how these interrelated factors affect the long-term wildfire threat poses a challenge to managers in the WHI. For instance, Hydro-Québec, the public utility responsible for electricity production, transmission, and distribution in the province of Québec, Canada, intends to maintain a wildlife connectivity corridor within a proposed 735-kV hydroelectric powerline. In an experimental measure designed to minimize the impacts to boreal woodland caribou (*Rangifer tarandus*) a species listed as threatened under the Canadian *Species at Risk Act* (Environment Canada, 2012) and vulnerable under the provincial *Loi sur les espèces menacées ou vulnérables* (ÉRCFQ, 2013), Hydro-Québec is proposing to raise the conductors of the powerline above the vegetation for a distance of ∼10 km. Hydro-Québec will then preserve vegetation cover within this section of the powerline right-of-way, rather than removing it, as is the standard operating practice.

Retention of vegetation within the powerline right-of-way, however, creates the possibility of placing the goals of wildlife conservation and infrastructure protection into opposition. The presence of vegetation is intended to reduce the negative effects of linear disturbance on caribou behavior and habitat selection (Dyer et al., 2001, 2002; Lesmerises et al., 2013; 2004), providing connectivity between patches of high-quality habitat. However, a vegetated right-of-way will increase the likelihood of wildfire and alter any consequent fire behavior, potentially resulting in more intense wildfire within the corridor than would occur in a cleared right-of-way. Greater fire intensity increases the difficulty of wildfire suppression (Anderson, 1981) and, by extension, the potential severity of damage of wildfire to the powerline. To ensure power grid resilience, it is imperative that managers have a means of assessing the wildfire threat within the connectivity corridor area throughout the expected 100-year lifespan of the powerline (Arab et al., 2021).

In response to this management need, we developed a flexible method for assessing current and future wildfire activity that combined the strengths of wildfire simulation and forest landscape composition modeling. Specifically, our objectives were to (1) assess wildfire threat (burn probability, fire intensity, fireshed) to the planned connectivity corridor and (2) define the characteristics and likely locations of ignitions posing a threat to the connectivity corridor, both over the next 100 years. To do so, we formulated a suite of possible future landscape scenarios to examine the interacting influences of climate change, vegetation, and forest management activity on wildfire threat to the corridor. Our analysis provides a means to quantify the magnitude of wildfire threat despite uncertain future conditions, as well as grounds for reflecting on potential mitigation measures, allowing managers to determine how much wildfire risk they are willing to accept for a project in which caribou conservation and wildfire mitigation are seemingly at odds.

STUDY AREA

The study area, located in the North Shore region of eastern Québec, is centered on the caribou connectivity corridor (49°34′5.5″ N, 69°25′44.9″ W) and includes nearly the entire extent of the planned 262 km Micoua–Saguenay powerline (Figure 1). We delimited a circular area with a 150-km radius for analysis, with an additional 30-km buffer region to avoid edge effects (Parisien et al., 2005). Terrain within this area consists of an intermix of upland forest, wetland areas, and lakes, with elevation ranging from sea level to points exceeding 1000 m (mean elevation: 444 m). Mean annual temperature for the region is 0.1°C (range from −3.9 to 3.6°C) and total mean annual precipitation is 1011 mm (range from 783 to 1224 mm).

Climatic and vegetation conditions vary along a roughly north–south gradient and include a strong maritime influence, with greater humidity, lower summer precipitation, and typically higher temperatures at greater proximity to the St. Lawrence River. The vegetation is predominantly boreal, but includes a small component of the mixedwood forest region of the northern temperate forest. The area lies within three bioclimatic domains designated by the dominant vegetation type: the balsam fir-white birch (*Abies balsamea* L. (Miller)–*Betula papyrifera* (Marsh.)) domain in the southeast along the St. Lawrence, the black spruce (*Picea mariana* [Mill.])–feathermoss domain in the north, and the balsam fir–yellow birch (*A. balsamea L.* (Miller)–*Betula alleghaniensis* (Brit.)) domain running along the Saguenay River to the south (Saucier et al., 2009).

Both natural (i.e., fire and insect outbreaks) and anthropogenic disturbances are common in the study area. The fire regime is currently dominated by large, high-intensity wildfires, with long wildfire return intervals of ∼400 years (Boulanger et al., 2014). The fire season extends from April to early October, although the bulk of wildfires and total area burned occurs in June. Lightning-caused fires account for 87% of the total area burned and primarily occur in the summer; spring fires tend to be human caused and contribute to a much smaller proportion of wildfire activity. Recurrent (every 30–40 years) spruce budworm outbreaks represent a second major natural disturbance, mostly in the southern mixed woods (Boulanger et al., 2012). Forest management, notably clearcut harvesting, is also exerting an extensive influence on this region (Fourrier et al., 2013), causing marked shifts in the forest to younger age classes and a more balsam fir-dominated landscape than would be expected under a wildfire-dominated disturbance regime alone (Bouchard & Pothier, 2011; Cyr et al., 2009).

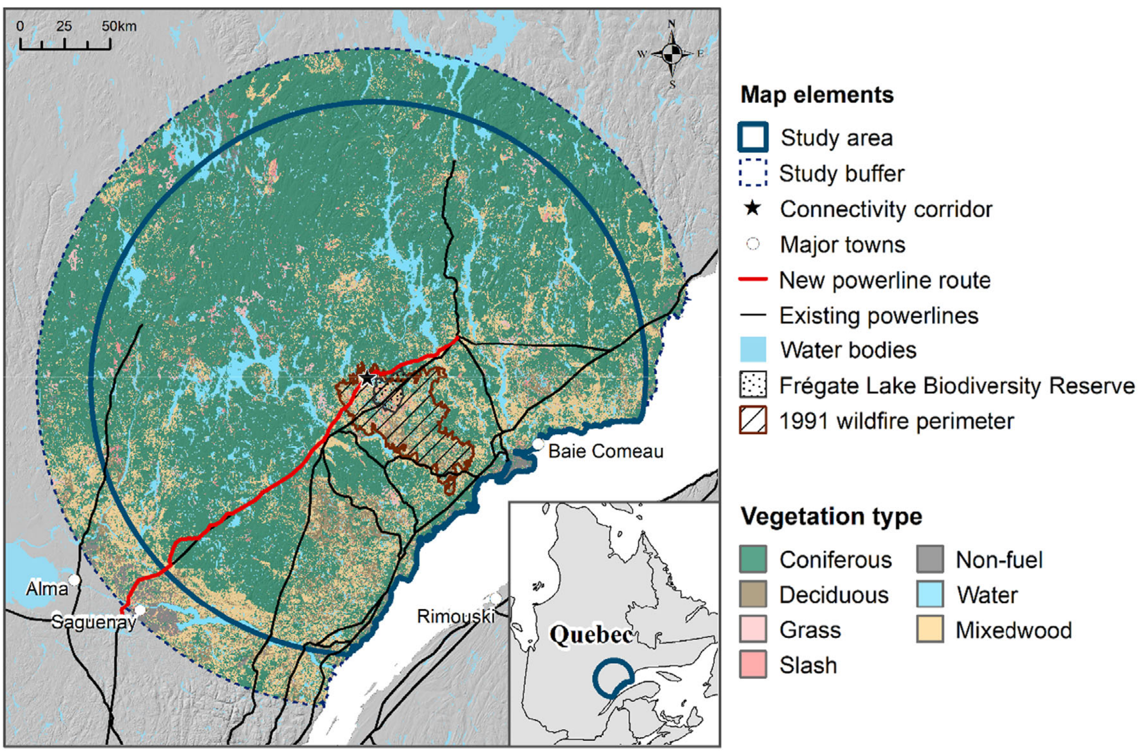

FIGURE 1 The study area representing the Micoua–Saguenay 735-kV powerline, relevant landscape features, and generalized vegetation types

Along the powerline, the planned 10 km connectivity corridor is northwest of a proposed biodiversity reserve at the northern edge of a large wildfire perimeter that burned in 1991 (Figure 1). Regeneration following the fire has been poor, with revegetation mostly consisting of patchy distributions of small trees intermixed within dominant, open ericaceous shrubs (Figure 2). In part because of this modest post-fire recruitment, the 1991 burned area has been largely undisturbed by humans (i.e., few roads and cabins, limited forestry activity). Despite the poor regeneration, some caribou use has been identified by telemetry data, and wildlife authorities in Québec expect increased usage of this habitat as conifers grow and a low level of anthropogenic disturbances is maintained. The connectivity corridor has therefore been located to maintain caribou movement between high-quality habitats to the northwest (not shown in Figure 1), and the biodiversity reserve, along with the regenerating burn in the southeast.

METHODS

We appraised both present and projected wildfire threat using the Burn-P3 wildfire simulation model (Parisien et al., 2005). As a Monte-Carlo fire simulation software, Burn-P3 relies on a series of static and probabilistic inputs, along with deterministic fire growth calculated using the Prometheus fire growth engine (Tymstra et al., 2010). Prometheus calculates fire growth based upon fuel types, fire spread equations, and weather indices of the Canadian Fire Behavior Prediction (FBP) and Fire Weather Index (FWI) systems (Forestry Canada Fire Danger Group, 1992), which are then iterated over in Burn-P3 to model wildfire behavior for many thousands of possible outcomes for a single fire year. Burn-P3 can incorporate projections of future weather, vegetation composition, and fire regime characteristics from other models to describe possible future wildfire probabilities and behavior or use historically derived measures of these same factors to describe current wildfire threat.

In our framework, we combined this strength of burn probability (BP) modeling in Burn-P3 with forest landscape modeling in LANDIS (Scheller et al., 2007) to assess future patterns of wildfire as a function of vegetation change under two different climate forcing projections (RCP 4.5, RCP 8.5) and four forest management scenarios (static, no harvest, extensive harvesting, harvesting excluded in protected areas) at two projected time steps (2070, 2120), as well as under current conditions (2020). In the projected time steps, along with a subset of scenarios simulated for the 2020 time period (from this point forwards, baseline scenarios), we

FIGURE 2 Typical post-fire revegetation within the 1991 burned area as photographed in September 2019

used simulated climate data to derive daily fire weather, as well as fire regime descriptors (number of ignitions per iteration, duration of wildfire spread) modeled from that climate data (cf. Wang et al., 2016). Projected scenarios were compared with baseline scenarios. In contrast, for our assessment of current wildfire probability and behavior, we used historically derived climate and fire regime descriptors (from this point forwards, observed scenario). We compared outputs from projected time periods (years 2070 and 2120) against the baseline, rather than the observed, scenarios to avoid biases between the simulated and observed weather data, as per Wang et al. (2016). In total, we examined 19 scenarios of present and projected wildfire behavior and likelihood, as portrayed in Figure 3.

Fire likelihood and behavior modeling

Our inputs to Burn-P3 represented the flammable vegetation (i.e., fuels), topography, weather, and characteristics of wildfire ignition and spread unique to the study area, derived from historic and projected conditions. A full list of inputs used in the modeling process is provided in Table 1. We constructed Burn-P3 inputs for the observed scenario using the methods of Parisien et al. (2013) as detailed in Appendix S1. We calibrated model inputs by comparing model outputs from the observed scenario against historic wildfire data for the study area from 1980 to 2017 to ensure that the model produced realistic outputs.

Following input development for the observed scenario, fuels, daily fire weather, the number of annual ignitions, and duration of wildfire spread were modified to develop the baseline and projected scenarios as a function of time period, climate forcing, and forest management scenarios. Baseline scenario inputs were calibrated against historic conditions and compared with observed inputs to ensure consistency between baseline and observed scenarios. Daily weather conditions were simulated for 2020, 2070, and 2120 using the global climate model CanESM2 for RCP 4.5 and

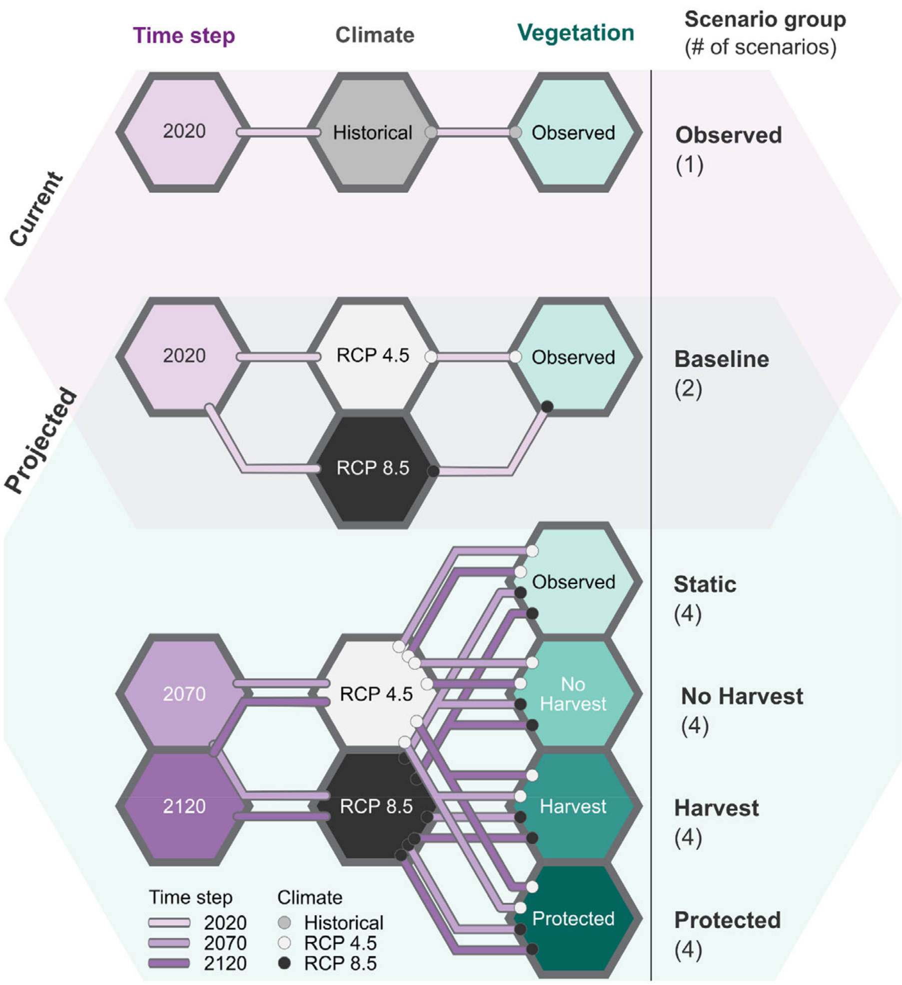

FIGURE 3 Wildfire simulation concept diagram showing the time step, climatic conditions, and vegetation grids used in our various scenario combinations

TABLE 1 Static and stochastic Burn-P3 inputs

Model input	Data type	Description
Static		
Topography	Continuous raster	Elevation (m)
Topographical wind speed and wind direction grids	Continuous raster (16 grids)	Influence of topography on wind direction and wind speed; produced for the eight cardinal directions
Fire zones	Categorical raster	Four geographically distinct fire regimes used to stratify ignition locations by season and cause
Weather zones	Categorical raster	Two geographic regions influenced by distinct climatic conditions (coastal, continental)
Fuels	Categorical raster	Canadian Fire Behavior Prediction System fuel and non-fuel types representing expected fire behavior; 15 total fuel types within the study area
Seasons	Setting	Start and stop dates for which fire weather, grass curing, and green-up change; two seasons used (spring and summer)
Minimum fire size	Setting	Minimum size at which fires are retained by Burn-P3. Set to 25 ha
Stochastic		
Ignition location grids	Continuous raster	Modeled probability of human and lightning ignition locations based on historic ignition data (1980–2017)
Ignitions by season, fire zone, and cause of fires	Frequency distribution	Proportion of fire ignitions by season, fire zone, and cause
Daily fire weather	Numeric list	Daily weather in which fires would be expected to ignite and spread, based on the Fire Weather Index System (i.e., when the daily value of the Fire Weather Index ≥ 13), partitioned by season and weather zone
Number of ignitions per iteration	Frequency distribution	Distribution of the number of fire ignitions burning within each iteration; based on historic (1980–2017) range of variability and projected to future conditions
Spread event days	Frequency distribution	Fire duration; derived from the number of fire weather days in which fires have the potential to achieve significant spread in both current and projected weather
Hours of burning	Frequency distribution	Daily hours in which fires can spread; set to vary between 5 and 6 h to average to ⅓ of total daylight hours in midsummer

Note: Static inputs are those that remain constant over all iterations within a scenario. Stochastic inputs reflect the variability in wildfire ignition location, spread duration, annual frequency, or weather conditions.

RCP 8.5 climate projections (van Vuuren et al., 2011) in BioSIM v.11 (Régnière & St-Amant, 2014; please refer to Appendix S1). Estimations of future fire regime variables, namely, the future number of annual ignitions and duration of wildfire spread for baseline and future time periods, were based on these daily fire weather projections, following the methodology of Wang et al. (2016) and Stralberg et al. (2018). Specifically, we used a linear regression model to relate the historic numbers of annual ignitions to the mean corresponding wildfire season wind speed and number of days in June, the month with the most fire activity, in which the Duff Moisture Code (DMC) exceeded 20. The DMC, an output of the FWI System, is an indication of moisture content of the forest floor, with values below 20 indicating wetter conditions with lower ignition likelihood (Anderson, 2010). Projected durations of wildfire spread were based on a relationship between the frequency distribution of consecutive fire-conducive weather days and observed spread (Wang et al., 2014). Readers can refer to Appendix S1 for additional details regarding the derivation of both of these metrics.

Vegetation conditions under each of the three climate-driven landscape management scenarios (no harvest, extensive harvesting, harvesting excluded in protected areas) were simulated using the forest landscape model LANDIS-II v.6.2 (Scheller et al., 2007). These simulations allowed us to assess how vegetation will change according to the interaction between the effects of increased anthropogenic climate forcing on stand dynamics and different forest management scenarios. Three vegetation scenarios were modeled using LANDIS-II: (1) harvest of all merchantable stands (considered to be those >60 years of age), aside from those in currently protected areas (extensive harvesting scenario, abbreviated as "Harvest" in figures); (2) harvest levels similar to the Harvest scenario but excluding all areas targeted under Québec's interim caribou protection program (MFFP, 2019) (harvest excluded from protected areas, abbreviated as "Protected" in figures); (3) no land management intervention (described as the "No Harvest" scenario). These harvesting scenarios do not attempt to predict accurate patterns of future forestry activity; instead, the first and third scenarios were designed to provide the maximal range of variation in which future vegetation may develop, with the second scenario designed to account for potential conflicts between caribou habitat conservation (i.e., protection of old-growth coniferous forest) and fire risk management. For these three scenarios, forest landscapes were also allowed to change according to species-specific modifications in growth and regeneration, under the respective anthropogenic climate forcing scenarios (RCP 4.5 and RCP 8.5). We did not simulate fire as an explicit disturbance in LANDIS-II because this would introduce a greater element of uncertainty into our modeling framework, due to the stochastic nature of where wildfire will ignite and spread in any one given year. As a result, simulated changes in forest landscapes are probably conservative, especially under increased anthropogenic radiative forcing in which fire ignitions and burned areas are projected to increase in the study area (Boulanger et al., 2014). An additional (4) scenario not involving forest landscape simulations was considered by holding current vegetation conditions constant (described as the "Static" scenario). Further details regarding the development of LANDIS-II inputs are provided in Appendix S2, as well as in Boulanger and Pascual Puigdevall (2021).

All scenarios in Burn-P3 were run using 20,000 iterations (i.e., 20,000 instances of a potential fire year). For the Static vegetation scenarios in 2070 and 2120, we allowed Burn-P3 to probabilistically select all ignition points, based on inputs describing the spatial likelihood of ignition. All subsequent Burn-P3 scenarios using alternative vegetation grids for these time steps were then run using ignition point locations and weather conditions identical to those simulated for the Static vegetation scenario of the same time period/climate condition combination. This feature, known as the "replay" function in Burn-P3, is used to allow a direct comparison of results among forest management scenarios of the same time period and RCP by removing changes generated by the stochasticity of the model.

Outputs and analysis

Current time period

To assess the wildfire threat for the observed scenario, we produced BP, fire intensity, and fire perimeter estimates from which specific spatial characteristics of burning and ignition locations can be extracted (Parisien et al., 2019). Burn probability is calculated as the number of times a pixel burns divided by the total number of iterations (20,000 for all scenarios) for that simulation. We displayed BP values for the observed scenario as "relative burn probability" by comparing the value of each pixel to the landscape mean BP. Relative BP categorizes pixels by the degree to which burning is either more or less likely than the landscape average; for example, pixels displayed within the −2 to −4 category are between two to four times less likely to burn than the average for the study area. The intensity (i.e., energy release, in kW/m) of wildfires modeled by Burn-P3 for the observed scenario was captured as the average intensity of the wildfires burning a pixel over all iterations. We mapped this measure, referred to here as "potential intensity" (PI), using four categories related to the FBP System (Forestry Canada Fire Danger Group, 1992) intensity classes and known changes in wildfire behavior: <2000 (surface fire), 2000–4000 (intermittent crown fire), >4000–10,000 (continuous crown fire), and >10,000 kW/m (extreme crown fire) (Alexander & de Groot, 1988; Alexander & Lanoville, 1989). Finally, we delimited the fireshed (i.e., the area in which fires that burn the corridor could originate; Thompson et al., 2013) by extracting the simulated wildfire perimeters that intersected the connectivity corridor, identifying the ignition points of these fires, and displaying a convex hull surrounding those ignition points.

Projected time periods

For the projected time periods and their baseline comparison points, we summarized and compared the mean BP and PI for the study area to that simulated within the connectivity corridor, defined as the pixels within the forested right-of-way usually cleared below the powerline infrastructure. As an additional analysis, we summarized the proportion of simulated wildfires burning within the corridor of each intensity class to describe the future likelihood of high-intensity wildfires within the corridor. As in the current time period analysis, we mapped the fireshed of the connectivity corridor for each projected scenario. We also computed the "fireshed burning ratio," a metric consisting of the ratio of the total number of times a pixel burned in simulation to the total number of times fires burning that pixel went on to burn the corridor. This newly devised metric, displayed within fireshed fire perimeters, can be considered a rough estimation of the likelihood that a fire burning within a pixel will affect an area of interest. We used this metric to describe the most problematic zones within the fireshed and assess changes not only to the size of the fireshed over time and scenarios but also the likelihood of danger posed to the corridor by wildfires burning in an area within the fireshed.

RESULTS

Current wildfire probability, intensity, and spread

In the observed scenario, the BP within the corridor ranged from 1.3 to 8.7 times less than the landscape mean (average study area BP = 0.00173; Figure 4a). PI within the corridor was, on average, 3.5 times less than the landscape mean (average study area PI = 5476 kW/m; Figure 4b). Fires within the corridor did burn up to 12,064 kW/m, although fires reaching this intensity class in any pixel within the corridor were rare (intensities >10,000 kW/m from all fires and corridor pixels occurring less than 1% of the time). Accordingly, the fireshed was relatively small. Here, 50% of the fireshed ignition points were within 1.6 km of the corridor, with distances ranging from 35 to 10,274 m (Figure 4).

Future wildfire probability, intensity, and spread

Burn probability varied by time period, anthropogenic climate forcing, and forest management scenarios, with the largest BP observed in 2120 under RCP 8.5 conditions in the scenarios retaining the greatest degree of coniferous forest (i.e., Static and No Harvest scenarios; Figures 5 and 6). In scenarios with harvesting (Harvest and Protected), much of this forest is removed and revegetated with less-flammable vegetation (Figure 6), resulting in lower mean BP within the study area. Mean BP within the corridor remained similar across vegetation scenarios under RCP 4.5 conditions (Figure 5a), but varied more widely

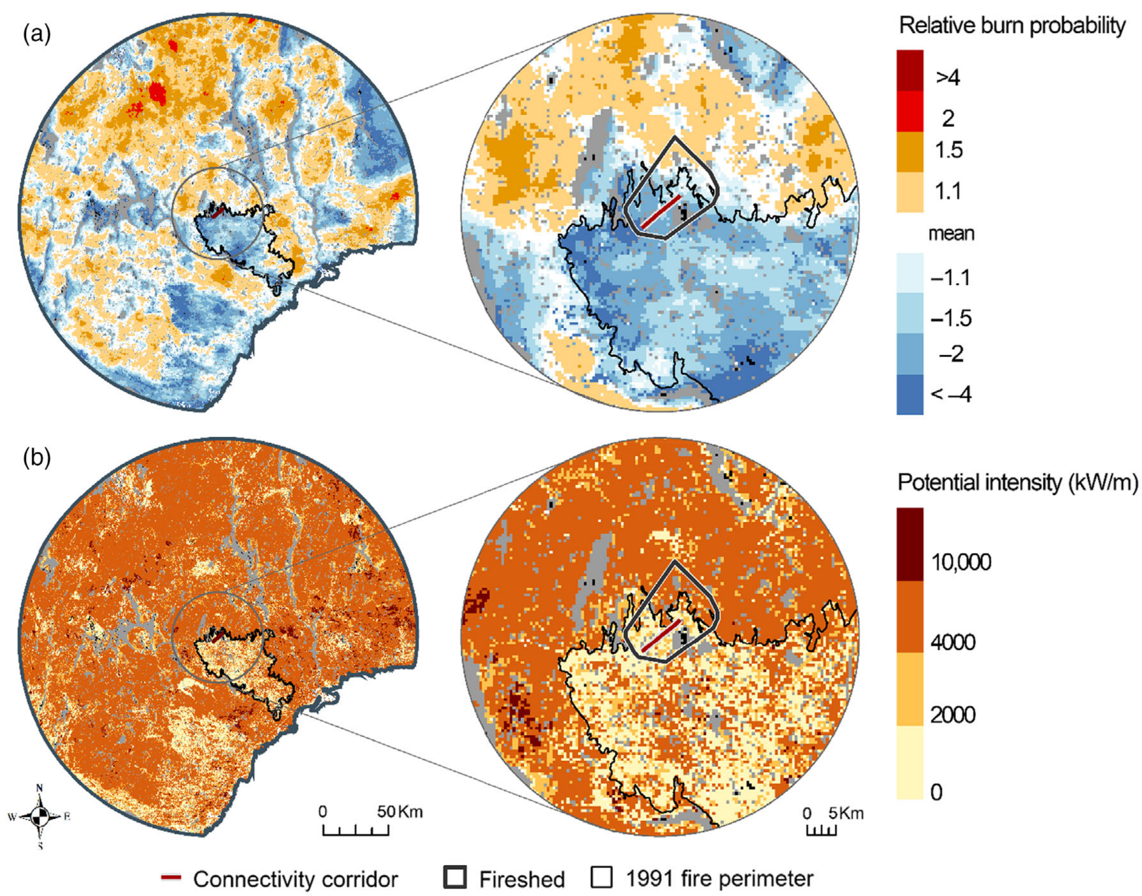

FIGURE 4 Observed scenario (a) relative burn probability (BP) and (b) mean potential fire intensity (PI) in the study area and immediate surroundings of the caribou corridor

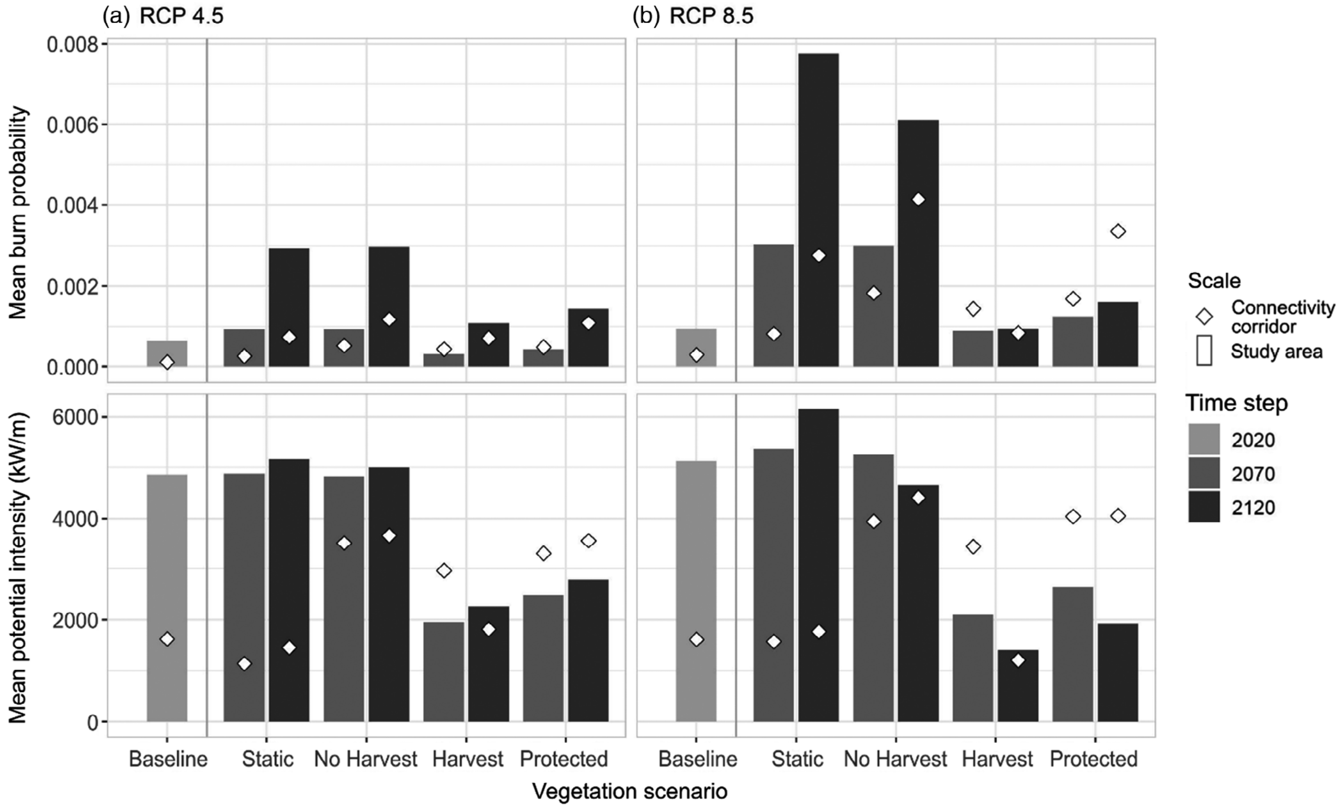

FIGURE 5 Mean burn probability (BP) and potential intensity (PI) under (a) RCP 4.5 and (b) RCP 8.5 climatic conditions for each projected vegetation scenario and time step compared with the baseline. Height of the bar represents the mean value for the study area while the diamond represents the mean value within the corridor

under RCP 8.5 conditions, with 2120 corridor BP values most reduced within the Harvest scenario (Figure 5b). In the RCP 8.5 Protected scenario, retention of coniferous forest in the area near the corridor (Figure 6), combined with conditions more conducive to wildfire ignition and spread, lent themselves to higher BP within the corridor area than in the rest of the landscape, although the BP in this scenario was lower than that observed in the Static and No Harvest scenarios. Despite this, the BP of both the landscape and the corridor within any given vegetation scenario typically increased with time and with greater anthropogenic climate forcing (Figure 5), with a noticeable exception of the RCP 8.5 Harvest scenario in 2120.

Variations in PI were much smaller among scenarios than the variation observed in BP. Within the corridor, a transition to more coniferous vegetation in the No Harvest and Protected scenarios increased PI by up to 2.7-fold of that modeled for the baseline (Figure 5). Although the PI of burning within the corridor remained below 4000 kW/m in more than half of the fires (Figure 7), mean PI within the corridor rose above 4000 kW/m in 2120 under RCP 8.5 in the No Harvest and Protected scenarios (Figure 5b). Lowest mean PI values within the corridor occurred with Static vegetation conditions, with the second-lowest found in the Harvest scenario, due to protection provided by poor forest recovery in the 1991 fire and extensive harvest, respectively (Figure 5). Wildfires burning at the highest intensity class (>10,000 kW/m) in the connectivity corridor remained relatively rare, regardless of the scenario (Figure 7).

Fireshed extent varied greatly among scenarios as a function of both forest management and climate scenarios (Figure 8). Firesheds and the area within which burning wildfires are likely to spread to the corridor (higher fireshed burning ratios) expanded with time under nearly every climate and forest management scenario. The largest firesheds and areas of high fireshed burning ratio (exceeding 0.5) were seen in the Static and No Harvest scenarios under RCP 8.5 (Figure 8). Indeed, a nearly 12-fold expansion in the fireshed and 7-fold expansion in the area covered by a high fireshed ratio was simulated between the 100-year (2020 to 2120) time step under RCP 8.5 conditions and the No Harvest scenario. In the Harvest scenario, the expansion of the fireshed was comparatively lower (RCP 8.5 conditions expansion: 2070 = 4.6 times baseline; 2120 = 2.92 times baseline; Figure 8), with the spatial extent of the fireshed under RCP 8.5 conditions in 2120 reduced in size from that simulated for midcentury (Figure 8).

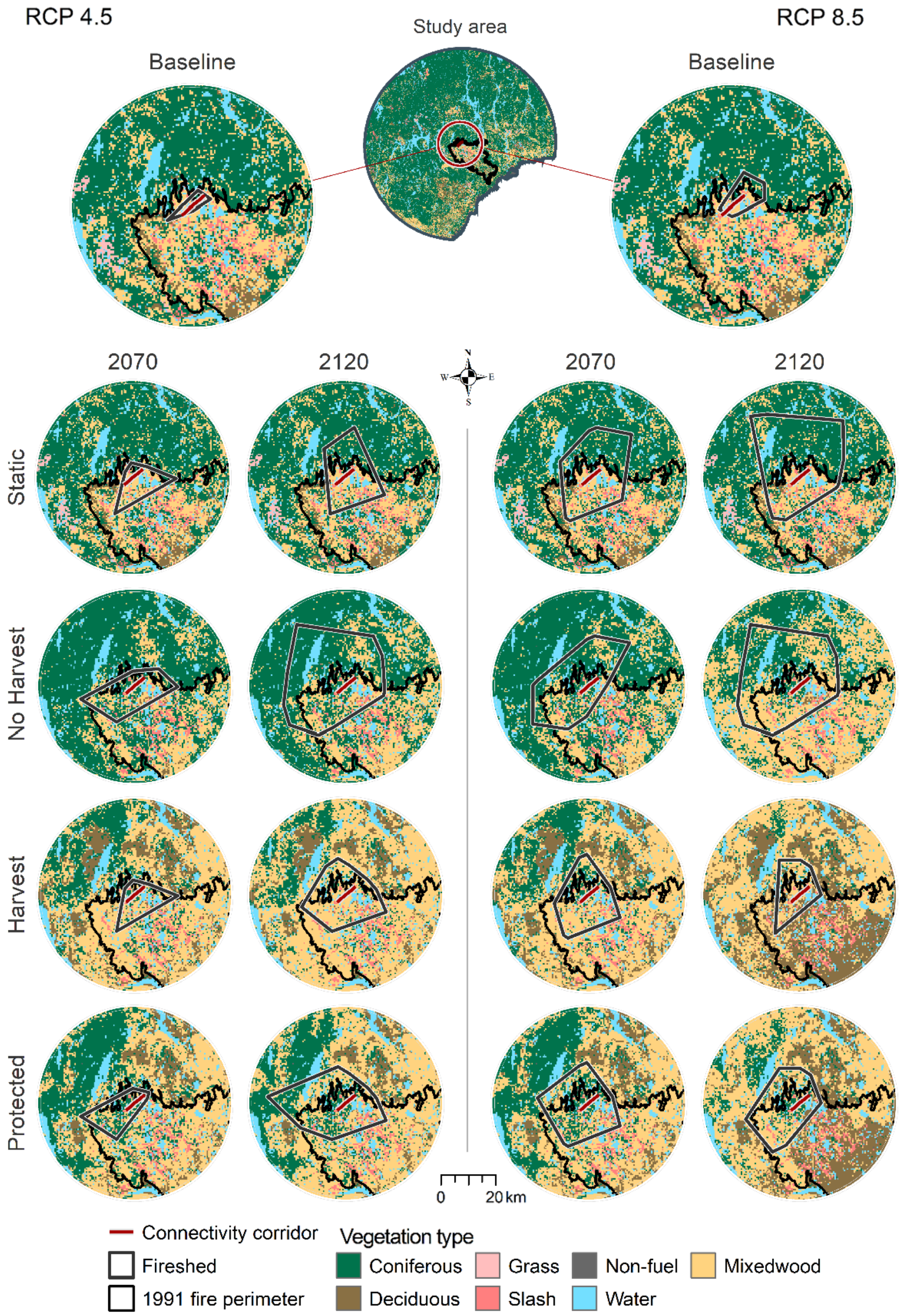

FIGURE 6 Modeled vegetation composition changes within and surrounding the corridor's fireshed for the baseline and projected scenarios within each vegetation grid, time step, and climatic condition combination

Regardless of the scenario, the highest density of fireshed ignitions was found within the area immediately surrounding the corridor, with most fires igniting within 5 km of the corridor (Figure 8).

DISCUSSION

We present a framework that combines fire simulation and forest landscape modeling to estimate an envelope of current and projected wildfire likelihood, intensity, and potential spread. Our framework builds upon the methods of previous modeling efforts (Stockdale et al., 2019; Stralberg et al., 2018; Wang et al., 2016) to consider climate-induced changes in landscape configuration (i.e., the spatial arrangement of fuels and non-fuels) along with the effects of forest management on wildfire activity. Our results suggest that the powerline caribou connectivity corridor is currently advantageously situated with regard to BP and PI. However, this situation is transitory. Fire hazard and the size of firesheds will increase in upcoming decades, due to interactions between fire-conducive weather and increased fuel load of forest vegetation. Despite this, modeled wildfire intensities indicate that fire suppression may be expected to remain effective (i.e., <4000 kW/m; Byram, 1959; Alexander, 1982) for most fires, regardless of scenario. In addition, harvesting may provide a catalyst for forest composition change to less-flammable forest types, should these stands be left to regenerate naturally, thereby mitigating future wildfire hazard. As such, future conditions may lend themselves to the use of wildfire mitigating fuel treatments in strategic locations to help reduce the likelihood of wildfire spread to the corridor.

Under current climate and forest conditions, prior disturbance provides protection from wildfire activity, due to a lower fuel load (Beverly, 2017; Héon et al., 2014; Parks et al., 2015). At initialization (2020), the high severity of the 1991 burn and subsequent poor regeneration within its boundaries produced a drastic negative feedback on BP and PI within the caribou corridor, compared with the surrounding landscape. The spatial positioning of the 1991 fire primarily downwind of the corridor further amplified this shielding effect, a phenomenon observed in other studies for burned areas or other natural firebreaks, such as water bodies (Nielsen et al., 2016; Stevens-Rumann et al., 2016). As a result, the area of problematic wildfires within the fireshed was predominantly restricted to a zone of ignition immediately surrounding the corridor for the current period, which greatly constrains the area to monitor to protect the corridor.

In projected time steps, we found that the effects of climate alone, as modeled in the Static scenario, largely overwhelmed the current resistance to burning within the 1991 wildfire perimeter. For instance, under RCP 8.5 conditions in the Static scenario, the BP of the corridor experienced up to a 9-fold increase from 2020 to 2120. These findings were a result of shifting climatic conditions promoting wildfire ignition and spread (Flannigan, Stocks, et al., 2009; Wang et al., 2017). Greater anthropogenic forcing under RCP 8.5 conditions spurred wildfire activity sufficiently to increase BP in 2070 to approximately that modeled for 2120 in RCP 4.5. These results are in line with a plethora of studies showing that projected increasing temperatures and drought conditions associated with RCP 8.5 will increase the number of fires (Boulanger et al., 2013; Flannigan, Krawchuk, et al., 2009; Flannigan, Stocks, et al., 2009; Weber & Flannigan, 1997) and the annual area burned (Coops et al., 2018; Flannigan et al., 2005; Hanes et al., 2019; Weber & Flannigan, 1997) within the boreal region of Canada. The effects of future climate on wildfire intensity were less pronounced, with the variability in PI among scenarios primarily being driven by changes in vegetation composition facilitated by forest management decisions (Hély et al., 2001).

The projected expansion of the firesheds, particularly in the primarily climate-based scenarios (i.e., Static and No Harvest scenarios) further underscored the projected increase in wildfire spread potential of future fire regimes. The increased area in which wildfires are likely to extend to the corridor (i.e., area of increased fireshed burning ratio), particularly under RCP 8.5 in the No Harvest scenario, delimited a larger zone in which wildfires are likely to pose a threat to the corridor, compared

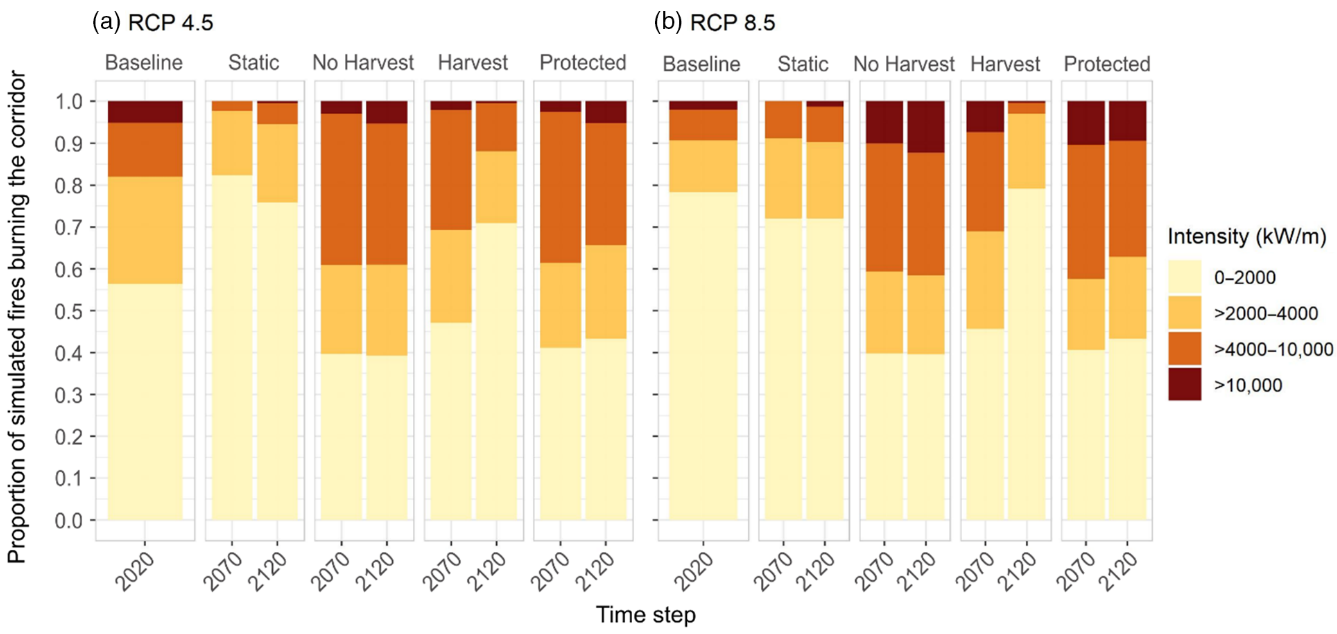

FIGURE 7 Proportion of wildfires burning within the connectivity corridor at each intensity class by time step and vegetation scenarios under (a) RCP 4.5 and (b) RCP 8.5 conditions

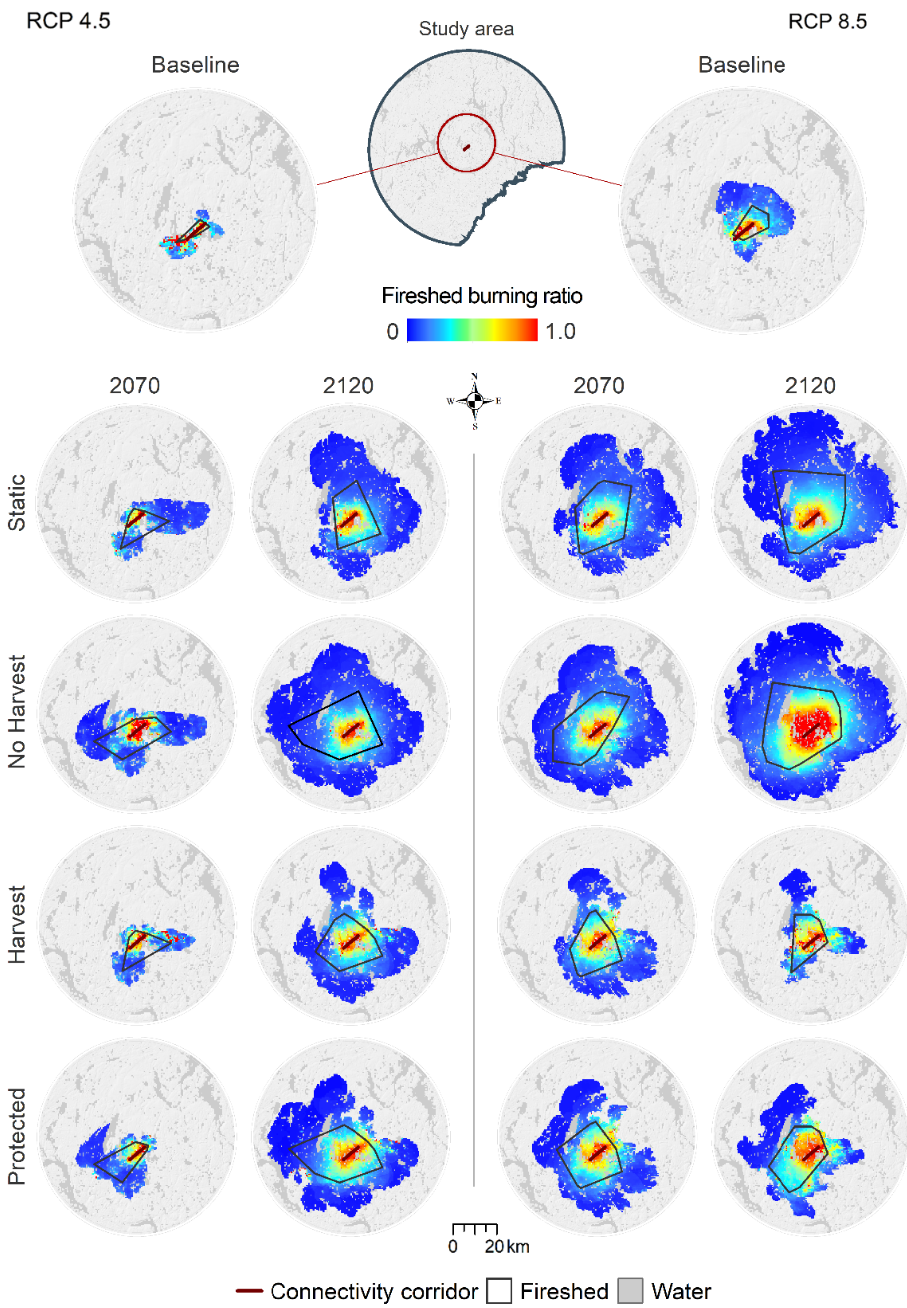

FIGURE 8 Fireshed burning ratio (i.e., the proportion of fires within a pixel that burned the corridor to all fires simulated within a pixel) shown for baseline and projected scenarios within each vegetation grid, time step, and climatic condition combination. The fireshed polygon (gray outline) indicates the convex hull surrounding fireshed ignition points with the colored areas encompassing the total fire spread from those ignitions

with rare, extremely long-distance spread events. It should be noted that the size and shape of the fireshed are influenced by such rare events (i.e., exceptionally large wildfires). For example, in the No Harvest scenario in 2120 under RCP 8.5, 75% of fireshed fires ignited within 4.5 km of the corridor, with only three wildfires reaching the corridor from >10 km away. Although an immense (e.g., >250,000 ha) wildfire affecting the corridor remains unlikely in the future, the Horse River Fire that burned into the town of Fort McMurray, Alberta in 2016 is a reminder that such rare events can be of high consequence.

Effective suppression could counteract climate-induced increases to wildfire threat. Increasing BP with time across most of our scenarios implies that fire suppression workload will grow during the lifetime of the corridor (Flannigan, Stocks, et al., 2009; Podur & Wotton, 2010). Assuming sufficient fire agency capacity to tackle the increasing workload, our model simulations suggest that, in most cases, direct attack of the fire front may be possible for most wildfires that would affect the corridor, thanks to the relatively lower flammability of surrounding vegetation. Simulated wildfires burn the corridor at intensities less than 4000 kW/m more than 50% of the time, regardless of the scenario. The threshold value of 4000 kW/m is associated with the transition from intermittent crown fire to continuous crown fire (Alexander, 1982; Byram, 1959). Suppression efforts at intensities between 2000 and 4000 kW/m typically require a mix of ground and aerial resources to control a wildfire's spread (Wotton et al., 2017), but are generally expected to be effective. However, extreme weather leading to extreme fire behavior and limitations on fire suppression effectiveness remains a distinct and hazardous possibility (Podur & Martell, 2007; Podur & Wotton, 2010).

Should a wildfire escape suppression, the magnitude of impact to the powerline will be driven by fire behavior characteristics, such as rate of spread and intensity. Assessing the degree of impact of fires to the powerline infrastructure is inherently difficult, due to challenges in assessing both first-order effects (i.e., the structural damage to the infrastructure) and second-order effects (i.e., the impact on people caused by resulting power outages). However, quantifications of fire impacts to powerline infrastructure have been attempted using expert knowledge, with the magnitude of impact relativized and weighted to allow comparison of fire effects across a variety of resources and assets (please refer to McFayden et al., 2019; Scott et al., 2013). In these estimations, the average PI within the corridor across most of our future scenarios would be assigned a value of −80 (range −100 to +100 for worst possible loss to greatest possible positive impact; intensity range ~3000–10,000 kW/m) by Scott et al. (2013), based on their assessment of the Bridger–Teton National Forest of Wyoming, USA. In contrast, these average PIs would be assigned a value of 100 (range 0–100 for no impact to greatest possible impact; intensity range > 2000 kW/m) by the assessment of McFayden et al. (2019) for the province of Ontario, Canada. As such, expert opinion from these other areas would suggest that wildfires burning under future conditions could be of high consequence to the powerline, should suppression efforts be ineffective.

Although changing climate will create weather conditions more conducive to wildfire ignition and spread, the effect of climate on vegetation succession is expected to generate negative feedback on wildfire activity. In our No Harvest scenario, climate-induced changes to forest succession prompted an observable shift from highly flammable, coniferous-dominated fuel types to vegetation that is less hazardous for wildfires, even without the influence of a disturbance catalyst. Longer growing seasons and warmer temperatures provide temperate deciduous species with a competitive advantage over cold-adapted boreal conifers (Fisichelli et al., 2014), potentially leading to a more mixedwood forest type in the future in these areas. Alternatively, climate-induced changes could produce more open woodlands following regeneration failures in coniferous species such as white spruce, black spruce, and balsam fir (Boulanger et al., 2017, 2019). In our scenario without harvesting (No Harvest), shifts to less-flammable vegetation were not sufficient to mitigate the climate-induced increase of wildfire activity. In contrast, extensive harvesting (Harvest, Protection) acted as a catalyst for vegetative changes (Boulanger & Pascual Puigdevall, 2021; Brice et al., 2020; Tremblay et al., 2018), moderating the climate-induced increase in BP and PI to reach approximately baseline levels by 2120 in our Harvest scenario. This finding is consistent with numerous other studies showing disturbance-mediated negative feedback on future wildfire activity (Chaste et al., 2019; Krawchuk & Cumming, 2011; Stralberg et al., 2018; Terrier et al., 2013; Wang et al., 2016).

Management implications

The process of analyzing future wildfire threat is inherently subject to uncertainty due to the complexity of projecting climate, vegetation, and disturbance regimes. By creating an envelope of conditions within which future wildfire behavior and probability conditions could lie, we attempted to bracket this uncertainty to help guide management actions. Given that the area occupied by the powerline caribou connectivity corridor is, at present, unlikely to burn at a high intensity, our analysis provides insight into when, and under what future conditions, wildfire likelihood and potential intensities could shift to unacceptable levels and endanger infrastructure. Although management decisions will need to be based on individual or organizational risk tolerance, or as a compromise between infrastructure risk and environmental benefits, our analysis framework also offers some paths for wildfire risk mitigation.

The projected reduction of highly flammable, coniferous vegetation within our study area under interacting conditions of harvest and climate change presents an opportunity for wildfire risk management. Fuel management, through activities including thinning, pruning, clear-cutting, or prescribed burning, are frequently used to mitigate the risk to valuable resources vulnerable to wildfire (Amiro et al., 2001; Beverly et al., 2020). Typically, fuel treatments have a transitory effect on wildfire hazard, as natural succession gradually returns a disturbed area to its predisturbance wildfire likelihood (Beverly, 2017; Parks et al., 2015; Peterson et al., 2004). By implementing fire mitigation in the form of fuel treatments, managers can take advantage of future climatic conditions that will promote less-flammable vegetative landscapes.

It is important to note that the disturbance imposed by fuel treatments could reduce habitat quality for caribou (Barber et al., 2018; Whitman et al., 2017), due to caribou reliance on disturbance-free old-growth coniferous forests (Faille et al., 2010). It would be imperative that the placement of fuel treatments not negate the positive impact on caribou habitat connectivity produced by the corridor. Instead, fuel treatments could be discerningly designed and placed using optimization methods (Chung, 2015; Pais et al., 2021; Yemshanov et al., 2020). This would allow them to be placed in areas that would provide barriers to wildfire ignition and spread (Palma et al., 2007) and maximize the reduction in wildfire threat, while simultaneously generating the least amount of possible impact to caribou habitat quality and connectivity. This precautionary approach may be especially warranted in areas such as ours, where long historic fire return intervals (in our area ~400 years) may have not allowed caribou behavioral adaptations that cope well with timber harvest (Lafontaine et al., 2019).

Our framework can be reproduced to perform long-term wildfire threat assessments for any valuable resource, such as essential infrastructure, habitat patches, or conservation measures situated in fire-prone areas. The flexibility provided by combining wildfire simulation and forest composition modeling confers ample opportunity for managers to assess current and projected wildfire likelihood and behavior using scenarios tailored to their unique needs and circumstances (Parisien et al., 2019). These analyses are complimented by the newly developed fireshed burning ratio, which has proven to be useful in highlighting areas that are more likely to carry wildfires that pose a threat to infrastructure of interest. Problematic areas identified by this analysis can be used in combination with BP and PI hazard analyses to identify where wildfire mitigation, such as fuel treatments or rapid suppression action, may be most acutely required to prevent spread to a protected resource.

Limitations

Modeling wildfire and forest succession using different models (Burn-P3 and Landis-II) allowed us to take advantage of their respective strengths. However, this approach is limited in that we did not allow wildfire itself to directly affect vegetation through time, to remove an element of stochasticity from our vegetation grids. Had we included wildfire as a disturbance agent between our time steps, recently burned areas would have further contributed to the decline in landscape BP and PI due to negative feedbacks of less-flammable, burned areas on wildfire activity (Héon et al., 2014; Krawchuk & Cumming, 2011). Furthermore, recurrent spruce budworm outbreaks, as simulated within LANDIS-II in this study, might temporarily increase fuel load in highly impacted stands, resulting in transient impacts to fire intensity, burn probabilities, and fireshed characteristics shortly after their occurrence (Watt et al., 2020). That said, given that climate-induced changes are likely to decrease host biomass (mainly balsam fir) in this area (Boulanger & Pascual Puigdevall, 2021), spruce budworm impacts on burn probabilities should gradually weaken with time and radiative forcing.

Several elements affecting the possibility of wildfire ignition and behavior, which we held constant across time periods, will change in the future. For example, wildfire seasons are likely to lengthen with a changing climate (Wotton & Flannigan, 1993), affecting seasonal patterns in wildfire behavior. Similarly, spatial patterns of wildfire ignition are also likely to shift due to changing patterns of human land use and management decisions (Chas-Amil et al., 2015). Although we implicitly included the influence of initial attack and suppression on fires in our Burn-P3 simulations by exclusively modeling ignition and spread of escaped wildfires, the direct influence of suppression is not explicitly modeled. Initial attack may become more effective in the future or, conversely, changing fire regimes could overwhelm suppression resources (Fried et al., 2008; Hope et al., 2016; Podur & Wotton, 2010). We justify holding these inputs constant due to the highly uncertain nature and lack of understanding surrounding the projection of these factors into the future. As such, as our understanding expands and new data become available, refinement of the models in future time periods may prove worthwhile to reduce uncertainty in the risk assessment process.

CONCLUSIONS

In the boreal forests of Canada, essential infrastructure projects, such as the installation of a new powerline, can be at odds with ecological goals such as the conservation of woodland caribou. By mitigating the negative effects to caribou and other wildlife, investment in innovative conservation measures, such as the connectivity corridor examined in this study, can present a compromise between seemingly opposing goals. However, managers are unlikely to accept such inventive solutions if they come at substantially increased risk of damage due to natural disturbances such as wildfire, reducing the life span of their investment. By comparing the potential likelihood and behavior of wildfires that could burn into the connectivity corridor to that characteristic of the landscape, we determined that the wildfire hazard within the corridor is currently relatively low. Over the next 100 years, the effects of climate change on fueling ignition and wildfire spread potential while simultaneously promoting less-flammable vegetation will have divergent impacts on future wildfire activity. As most wildfires burning within the corridor in our projections were moderate enough to respond to suppression efforts, the decision to implement hazard-mitigating fuel treatments in the area surrounding the corridor will largely depend on managers' risk tolerance. However, future climate conditions favoring less-flammable forests could provide an opportunity for effective, long-term fuel treatments, although such treatments would need to consider wildlife habitat requirements. Our study provides a perspective on how the interaction between climate and forest management will influence both the likelihood and intensity of current and future wildfires. As a result, our framework can be used to address the uncertainty of future wildfire regimes, thereby supporting risk-based decision-making for other infrastructure or conservation projects vulnerable to wildfire.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data and code (Dawe, 2022) are available from OSF: https://doi.org/10.17605/OSF.IO/BE97T.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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