

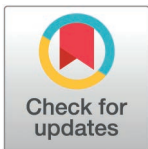
RESEARCH ARTICLE

A network optimization framework for fuel break planning in wildfire-prone landscapes: Accounting for fuel break failures and wildlife conservation goals

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Data availability statement: The Python code to generate the wildfire propagation graphs and relevant model data from the wildfire simulation

Abstract

Large wildfires are a dominant type of disturbance in North American forests that have caused significant environmental impacts and economic damages. A potential approach to mitigate wildfire spread risk is to segment the landscape with fuel breaks or similar areas with reduced fuel content. However, fragmenting the landscape may undermine other ecosystem services, such as the provision of wildlife migration routes. We present a mixed-integer programming fuel break planning model that minimizes wildfire hazard while protecting migration routes for an endangered wildlife species population (woodland caribou, *Rangifer tarandus caribou*). Our model applies the network optimization concept and minimizes the expected burn area in the landscape while protecting a target proportion of the wildlife migration routes. We depict the landscape as a network of patches with fuel and track the impact of fuel breaks across a large set of predicted fire spread scenarios where each scenario is conceptualized as a fire propagation graph. We formulated the fuel break allocation as a scenario-based, mixed-integer optimization problem and used the fuel break widths to track the potential failures of the fuel breaks to contain the fire spread. We also considered a planning problem that minimized the expected area of the largest fires and fuel connectivity in the landscape. For given fire hazard reduction goals, the optimal solutions are those with the least disruptive impacts on the wildlife migration routes. We implemented the approach for the planning of wildfire mitigation in the Red Rock-Prairie Creek area of Alberta (Canada), a fire-prone landscape with the presence of caribou populations. The proposed approach reduced the wildfire spread potential in the area with a trade-off of moderate impacts on known caribou migration routes. Such a methodology is timely to help develop strategies for reducing wildfire

data is available from <https://github.com/nliu-cfs/FPT-plus>. The relevant input and mapping data and the GAMS model code for problems 1–6 can be found in S4 Appendix.

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hazard in fire-prone forest landscapes while achieving conservation management goals in other regions.

Author summary

Wildfires represent the most catastrophic disturbance type in North American forests and have caused significant damage and claimed human lives. The implementation of fuel breaks has been considered a strategic measure aimed at reducing fire hazard; however, designing a cost-effective fuel break system is challenging due to unpredictable fire behavior and the uncertain capacity of fuel breaks to stop wildfire spread. Fragmenting the landscape with fuel breaks may also impact other ecosystem services, such as the provision of undisturbed areas to support seasonal wildlife migration. Thus, there is a significant need to develop new methods to assist with the planning and assessment of trade-offs between the capacity of fuel breaks to reduce wildfire hazard versus protecting other ecosystem services. In this study, we applied the fire propagation graph concept to formulate a spatial fuel break planning model that minimizes the spatial connectivity of fuels in a landscape while accounting for potential failures of fuel breaks to contain fire spread. We further applied the Conditional Value-at-Risk concept to address the uncertainty of possible fire spread in fuel break planning decisions. Our model enables a consideration of the trade-off between fuel break width and potential failures to contain fire spread. Our methodology helps develop strategies for reducing wildfire hazard while maintaining key ecosystem services, such as the protection of wildlife migration routes, and could assist in the strategic planning of wildfire mitigation in fire-prone landscapes.

1. Introduction

Wildfires represent the most frequent natural disturbance type in the montane and boreal forests of North America [1,2] and have caused significant damages to human infrastructure and commercial timber supply [3,4]. Future damages from wildfires and associated mitigation costs are expected to increase due to climate change [5–8], as evidenced by the record-breaking 2023 fire season in Canada [9]. These circumstances call for the implementation of strategic measures to reduce wildfire hazard, such as the removal of forest fuel and disrupting its connectivity across forest landscapes [10–12]. In this context, strategic fuel breaks (*cf.* [13]), which prescribe the complete removal or reduction of vegetation and fuel, have emerged as a practical means to decrease wildfire intensities to levels where they can be contained [10,11,14,15]. These fuel breaks – strategically placed area treatments or fuel-modified zones – have been implemented in parts of western Canada and USA [16–20].

At a broad scale, these fuel breaks are intended to strategically segment a landscape, thus localizing potential fire damage and reducing the capacity of wildfires to

spread over long distances [10–12]. However, designing effective fuel breaks is challenging [15,21,22] because of uncertainties associated with the occurrence of fires and the capacity of fuel breaks to stop fire spread under extreme weather, when firebrand spotting may cause rapid fire spread [23–27]. As a practical matter, fuel breaks must be allocated to individual forest sites, but the combined impact of the fuel breaks on fire hazard must be assessed at a whole-landscape scale. This aspect is difficult to address in planning because wildfire risk shifts in rapidly changing weather, altering which fuel breaks are likely to provide the best mitigation locally and, in turn, the hazard reduction potential of the entire system of fuel breaks.

In Canadian boreal forests, where long-distance firebrand spotting is common, fuel breaks must be sufficiently large to serve as effective barriers [26]. Collectively, a system of fuel breaks also represents a significant landscape-scale disturbance that may impact other ecological processes which rely on forest patch connectivity, such as the movements of wildlife species that require undisturbed habitat to maintain their seasonal behaviour. This is the case for the Southern Mountain population of woodland caribou (*Rangifer tarandus caribou*; hereafter caribou) in Alberta, Canada. In recent decades, caribou populations have declined due to increased predation caused by anthropogenic fragmentation of caribou habitat [28,29]. Nationwide, woodland caribou is listed as threatened under the Species at Risk Act [30].

Fuel breaks also provide habitat for other ungulate species who forage on early plant regrowth [31] and become more attractive to predators which may also kill caribou. Areas with reduced fuel content provides predators with easier access within habitat areas, further contributing to caribou decline [31–33]. In the West Central region of Alberta, Canada, caribou migrate seasonally from high-elevation areas in summer to low-elevation foothills in winter [34,35], to forage and avoid predators [31,36]. By degrading the ability of caribou to use their preferred migratory corridors, fuel breaks could lead to the loss of sizeable portions of the winter caribou range in this region [37].

Ideally, the fuel breaks, while minimizing the wildfire threat, should pose the minimum impact to caribou migration, but achieving both management goals may not be feasible, particularly in regions where old coniferous forests pose both high burn hazard and remain the primary caribou habitat. In this situation, one needs to assess the trade-off between the anticipated reduction of wildfire hazard versus preserving the key caribou migration routes.

1.1. Assessing the trade-offs between fire hazard reduction and preserving wildlife migration routes

Historically, the planning of fuel treatments and wildlife conservation measures, along with associated assessments of potential trade-offs, have been assisted by optimization. Notable previous applications include the model of León et al. [38] that fragmented contiguous forest areas with fuel while protecting sites with wildlife habitat. The model of Carrasco et al. [12] estimated the impact of firebreak allocation and the reduction of wildfire damage on habitat losses in a landscape. The model of Nguyen et al. [39] aimed to reduce the connectivity of forest fuel and applied a set of simulated fire footprints to allocate firebreaks in a landscape under an uncertain fire regime. The models of Acuna et al. [40] and Troncoso et al. [41] considered timber harvesting as a way to implement fuel breaks and reduce landscape flammability.

Another common fuel treatment planning strategy aims to disrupt local fuel connectivity by controlling the number of adjacent forest patches with fuel [12,42–45]. Extending this idea, several studies have proposed allocations of fuel treatments with the stated goal of reducing the global fuel connectivity across a landscape. In these studies, the landscape was depicted as a network of patches with fuel, and the optimization models were designed to find the locations where fuel breaks would maximally degrade the connectivity of the landscape fuel network [46–49]. Achieving this objective required solving a critical node detection problem [50] that minimized the number of location pairs between which fire spread is possible.

In a related fashion, the concept of patch connectivity has been applied to manage the protection of wildlife corridors [51–53]. Common approaches have included allocating minimum-resistance and minimum-cost wildlife corridors [51,53–56] and maximizing the overall connectivity between patches with habitat in a landscape [12,51,56]. Conrad et al. [56] formulated an allocation of wildlife corridors as a connected graph problem. Similarly, the landscape connectivity

problem has also been formulated as a Steiner network problem [55,57] and embedded into broader forest management models featuring other forest planning objectives, such as harvesting [54,58].

To make mitigation effective against large fires such as those that occur in Canadian boreal forests, the capacity of the fuel breaks to stop long-distance fire spread assisted by spotting must be considered explicitly in modelling and planning workflows. This requirement presents a particular challenge to wildlife conservation objectives that has not been fully addressed in previous fuel treatment planning models. In this study, we address this shortcoming and propose a new optimization-based fuel break planning model that aims to reduce wildfire hazard while preserving known wildlife migration routes in the area. We apply the model in a landscape-level setting to find a strategic configuration of fuel breaks that minimizes fire spread connectivity with respect to a large set of uncertain wildfire occurrence outcomes while protecting a target portion of wildlife migration routes in a fire-prone landscape.

1.2. A graph-based approach to depict fire spread uncertainty and fuel break impacts

Fire behaviour in complex landscapes is highly uncertain. A common approach to depict this uncertainty is to simulate a large set of “what-if” scenarios with possible fire footprints and ignition locations within a burn year using a stochastic fire growth model that predicts fire spread as driven by weather, terrain and human activities [59–62]. However, these complex predictions (i.e., tens of thousands of spatial fire scenarios) rarely have been utilized to their full extent to address an important challenge in wildfire mitigation planning: the capacity (or failure) of the planned fuel breaks to stop long-distance fire spread [24,25,63]. A novel aspect of our approach is the conceptualization of a large set of ignition locations and fire footprints that depicts uncertain fire behaviour as a set of directed fire spread graphs, which we use in an optimization setting to find an effective configuration of fuel breaks. Following recent graph theory applications [49,64], we depict the fire spread sequences from ignition locations within the simulated fire footprints as fire propagation graphs (FPGs hereafter). An FPG is an acyclic graph with its root node in the fire’s ignition location and directed edges between adjacent nodes indicating the possible fire spread paths towards its perimeter (Fig 1A). Placing a fuel break within the FPG blocks the fire propagation in that location within the FPG (Fig 1B). Considering that each FPG is a discrete realization of a random fire occurrence and spread process, tracking the impacts of fuel breaks over a large set of equal-probability FPGs estimates the expected burn area (or damage) in the landscape. Compared to previous fuel treatment models based on the FPG concept [49,64] our methodology considers allocation of different fuel break types and can account for potential fuel break failures. Each fuel break type has a defined width that limits the maximum firebrand spotting distance that fuel break type could contain or, otherwise, indicates fuel break failure.

For each fuel break location across the landscape, we estimate the distribution of potential fire spread outcomes as a subset of FPGs overlapping that location. In turn, we characterize each location within each overlapping FPG in terms of burn intensity level using the outputs from the spatial fire growth model. For example, a fuel break of a particular width could stop the spread of a low-intensity fire that is depicted by one FPG but would fail to stop a high-intensity fire that is depicted by another FPG. Tracking fuel break failures in this manner has not been considered previously in a fuel treatment optimization context and helps address a shortcoming of our previous work [47,48] and related studies [64].

The principal objective of our fuel break planning model is to minimize the total burn area. However, we also explored an alternative problem that minimizes the fuel connectivity (and the corresponding fire spread connectivity). Previously, this problem has been formulated as a critical node detection problem that enforces transitive connectivity relationships between nodes in a fuel network [46–48]. Here, we present a new formulation that does not rely on transitive connectivity constraints and instead uses FPGs to track the fire spread connectivity between patches with fuel.

We applied the proposed models to a large forest landscape in West Central Alberta, Canada (Fig 2). In this landscape, we also evaluated the objective of protecting critical caribou migration routes in our fire mitigation scenarios. This associated objective minimizes the number of caribou migration routes fragmented by the fuel breaks. We assessed the

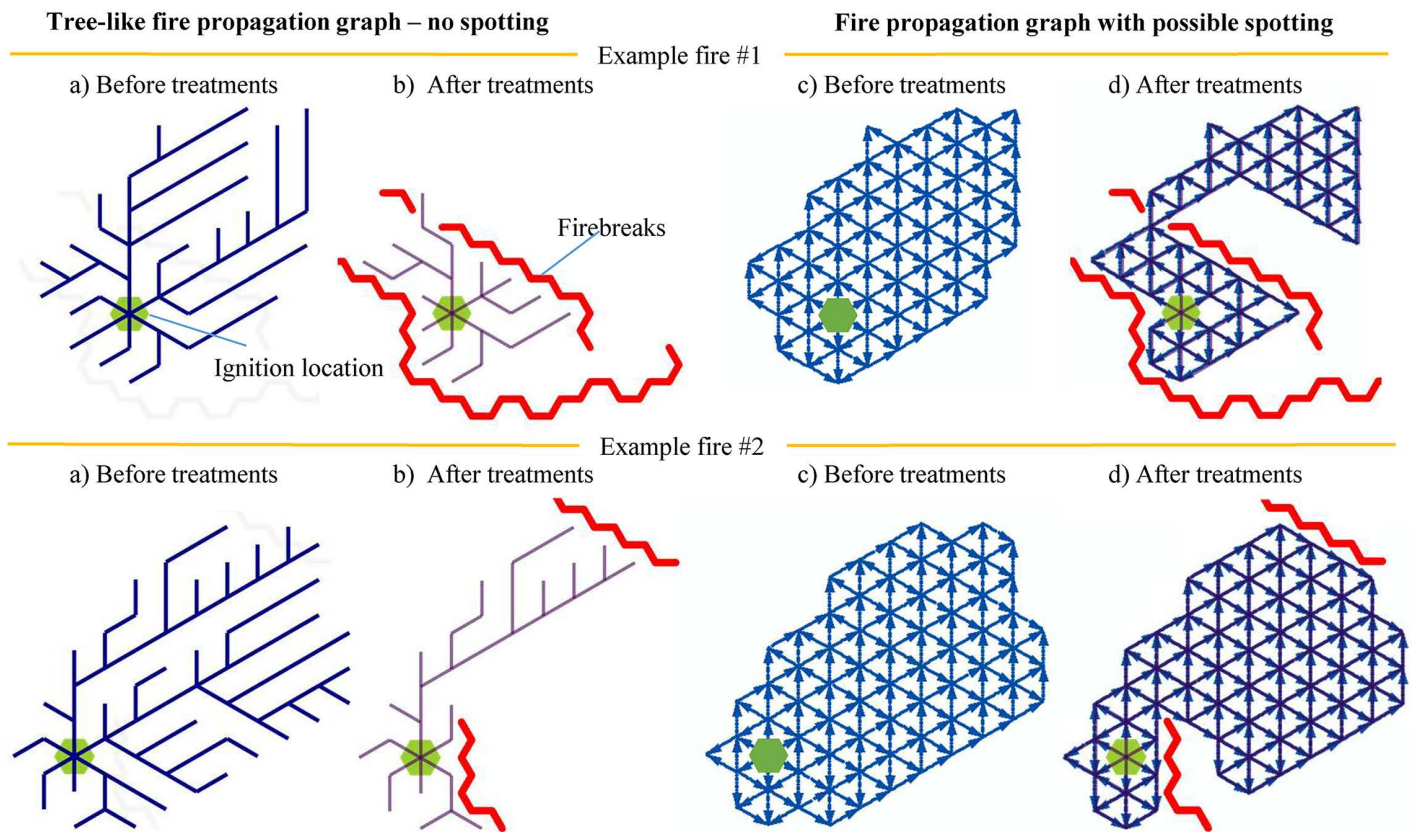


Fig 1. Examples of fire propagation graphs (FPG): a) a tree-like FPG with its root node in the ignition location; b) impact of fuel break placement on fire propagation through the FPG; c) a fully connected FPG that allows a fire to spread from multiple upstream locations; d) impact of fuel break placement on fire spread through a connected FPG.

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trade-off between the degree of caribou migration route protection and the reduction of fire spread potential provided by each allocation approach.

2. Materials and methods

2.1. Study area

The study area is in the Red Rock-Prairie Creek region of Alberta, Canada (Fig 2) and includes upper foothills and lower subalpine ecoregions, with elevations up to 1,750m in the southern portion of the region bordering the Rocky Mountains [70,71]. The region's forests are dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) at higher elevations, and subalpine larch (*Larix lyallii*) and lodgepole pine (*Pinus contorta*) at lower elevations. Mixedwood stands at lower elevations are dominated by aspen (*Populus tremuloides*), white spruce (*Picea glauca*) and lodgepole pine. The area has been used by forest industry for timber supply [71] and was subject to cyclical oil-and-gas exploration activities that have left a network of narrow linear forest disturbances [72]. The study area partially overlaps the range of the threatened Redrock-Prairie Creek caribou population [28]. During winter, these caribou migrate into our study area from higher elevations in the Rocky Mountains to the southwest in Alberta and British Columbia, where they spend the summer season.

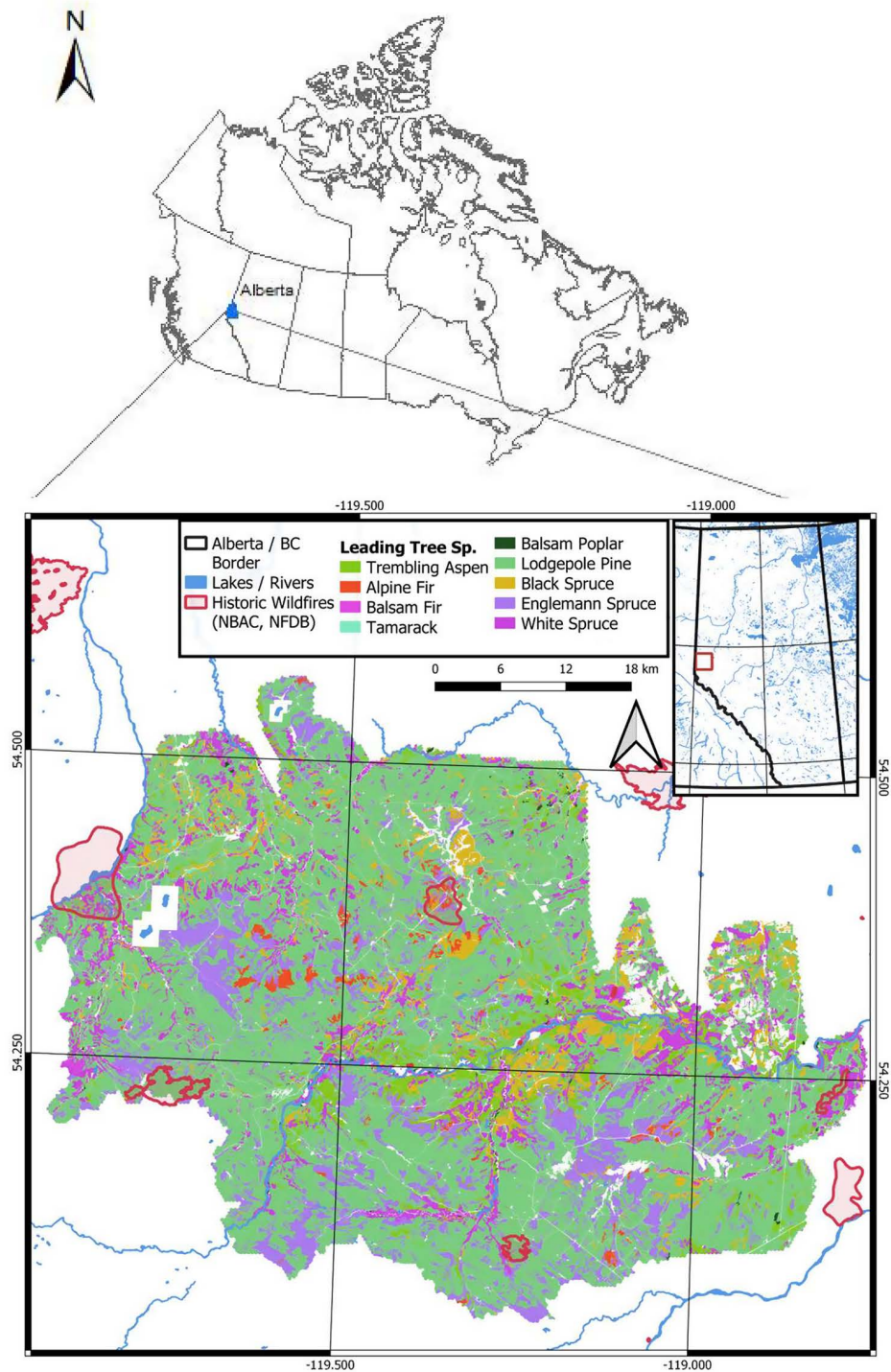


Fig 2. Study area in the Red Rock-Prairie Creek region, Alberta, Canada. Spatial data used: administrative boundaries [65]; historic fires [66,67], waterways [68]; land cover composition [69]. Mapping software used – ESRI ArcMap 10.

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Historically, the area has experienced frequent small to medium-sized fires and infrequent large fires [71]. Fire return intervals are estimated to be between 80 and 300 years at higher elevations in the southern part of the region and between 45 and 476 years in the lower elevation portions of the region [71,73]. The area is characterized by prevailing winds blowing from west-southwest to the east, which influences the dominant fire spread pathways (Fig 3A and 3B). An abundance of mature conifer forests has made the area highly susceptible to fires [71]. In the lower elevation areas, human-caused fires peak in May, while lightning-caused wildfires peak later in the summer. The higher elevation areas in the southwest experience mostly lightning-caused wildfires, with the peak fire season between May and August [74].

2.2. Simulating the fire regime in the study area

We simulated plausible fire regimes in the study area with a spatial fire growth model, which are commonly used for predicting wildfire behaviour in complex landscapes [60–63,75,76]. They have been applied in many regions, for example the Burn-P3 [77] and Cell2Fire [60] models in Canada and the FSim model in the USA [62]. Typically, these models can output location-specific fire behaviour information, such as fire footprints, ignition points, burn intensities and linear rates of spread [61,63,75,77].

We applied the Burn-P3 model [77], which uses the Prometheus fire growth algorithm [78]. The Prometheus algorithm is based on the Canadian Forest Fire Behavior Prediction (FBP) System [79]. Burn-P3 generates a single “burn year” as a stochastic replication. The ignition locations and daily fire weather conditions were based on draws from historical probability distributions for the study area. For each replication of a fire season, the model generated the ignitions and perimeters of individual fires. The fuel composition map was developed in accordance with the Canadian FBP System [80]. The likelihood of ignitions varied across the landscape and was derived from lightning density data [81] or, for human ignitions, based on proximity to roads as calculated from road network data (provided by Weyerhaeuser Ltd.; see details in S1 Appendix). We used 60,000 replications of a burn year at a 1-ha spatial resolution to account for the pattern of fuel and natural fire barriers.

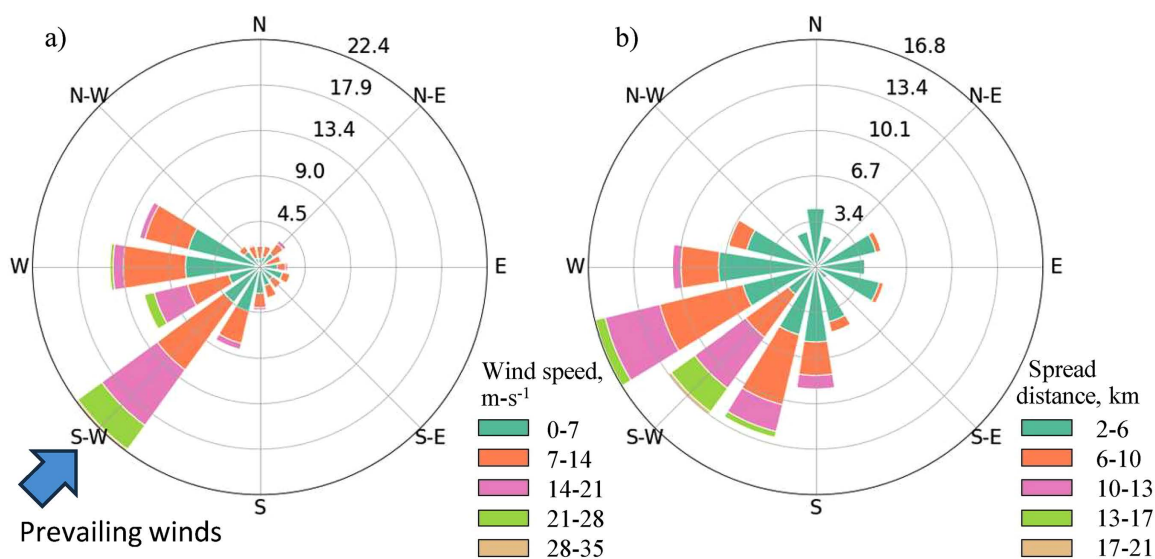


Fig 3. Wind rose diagrams: a) prevailing winds; b) fire spread directions between node pairs i,j across the study area.

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2.3. Fuel break planning with the FPG concept

Our fuel break planning problem considers a forest landscape as a network of N hexagonal patches with fuel (nodes i hereafter, $i \in N$), where each node i is connected to adjacent nodes j by directed edges ij (see Table 1 for symbolic notations). A wildfire can propagate through edges ij from a node with the fire's ignition location towards the nodes at the fire's perimeter (Fig 4A and 4B), although the actual fire propagation paths from the ignition location are unknown. We depicted the uncertain behavior of fires in landscape N as a large set F of fire occurrence scenarios. Each scenario f , $f \in F$, depicts the ignition location, the spatial fire footprint and location-specific burn intensity data. We assumed that each fire scenario f has equal probability of occurrence, $1/|F|$. The choice of a particular fire growth model is not pivotal to the formulation of our fuel break planning problem, as long as the model can adequately recreate the fire regime of the landscape according to current expectations.

Each fire f is characterized by its spatial footprint S_f and ignition location ϕ_f . For each location (node) i within the fire's footprint S_f , the fire growth model outputs provided burn intensity estimates, β_{fi} , in kW-m⁻¹. The fire growth model simulated

Table 1. Summary of the model variables and parameters.

Symbol	Parameter/ variable name	Description
Sets:		
N	Nodes (forest patches) i,j,k,l with fuel – potential fuel treatment locations	$i,j,k,l \in N$
E	Edges connecting adjacent nodes ij in landscape N	$E \subset N \times N$
F	Fire propagation graphs (FPGs) depicting the fire scenarios f	$f \in F$
G	Fuel break types g that can be allocated in edges ij	$g \in G$
R	Wildlife migration paths r through landscape N	$r \in R$
S_f	Nodes in the footprint of fire f	$S_f \subset N$
T_f	Edges ij – members of the directed propagation graph (FPG) for fire f	$T_f \subset N \times N$
ϕ_f	Node i with the fire's f ignition location (a singleton set)	$\phi_f \in S_f$
Ω_i	Nodes j – members of a fireplain around node i (potential spread destinations of fires ignited in i) – the union of all fire footprints S_f with their ignition locations in node i	$\Omega_i \subset N$
Ψ_{ij}	Set of edges ik,jk,il and jl that comprise the adjacent fuel break segments to the fuel break segment allocated across edge ij	$\Psi_{ij} \subset E$
Decision variables:		
y_{ig}	Fuel break type g applied to edge ij ($y_{ig} = 1$ if treatment type g applied to arc ij and $y_{ig} = 0$ otherwise)	$y_{ig} \in \{0,1\}$
u_{ij}	Binary variable defining that a fire could spread from node i to node j ($u_{ij} = 1$ and $u_{ij} = 0$ otherwise)	$u_{ij} \in \{0,1\}$
n_{fi}	Burn status of node i in fire scenario f ($n_{fi} = 1$ if node i in fire f retains burned status and $n_{fi} = 0$ otherwise)	$n_{fi} \in \{0,1\}$
q_r	Binary variable defining that caribou path r is intersected by a fuel break ($q_r = 1$ and $q_r = 0$ otherwise)	$q_r \in \{0,1\}$
μ_f	Conditional Value-at-Risk (CvaR) linearization auxiliary variable	$\mu_f \geq 0$
Z	Conditional Value-at-Risk (CvaR) linearization auxiliary variable	$Z \geq 0$
Parameters		
θ_{ij}	Number of incoming edges ij connecting the upstream nodes i to node j in fire propagation graph T_f	$\theta_{ij} \in [0;5]$
χ_{fig}	Binary indicator that fuel break type g is sufficient to stop the spread of fire f through node i ($\chi_{fig} = 1$ and $\chi_{fig} = 0$ otherwise)	$\chi_{fig} \in \{0,1\}$
c_{ig}	The cost of allocating fuel break type g in edge ij	$c_{ig} > 0$
B	Maximum fuel break area limit, km ²	$B > 0$
β_{fi}	Fire intensity in node i in fire scenario f , kW-m ⁻¹	$\beta_{fi} > 0$
σ_{ri}	Binary indicator that wildlife migration path r intersects the vicinity area around edge ij	$\sigma_{ri} \in \{0,1\}$
$q_{\max}$	Maximum proportion of wildlife migration paths r that can be interdicted by fuel breaks	$q_{\max} \in [0;1]$
ρ_r	Priority weight of wildlife migration path r (path length, nodes i)	$\rho_r > 0$

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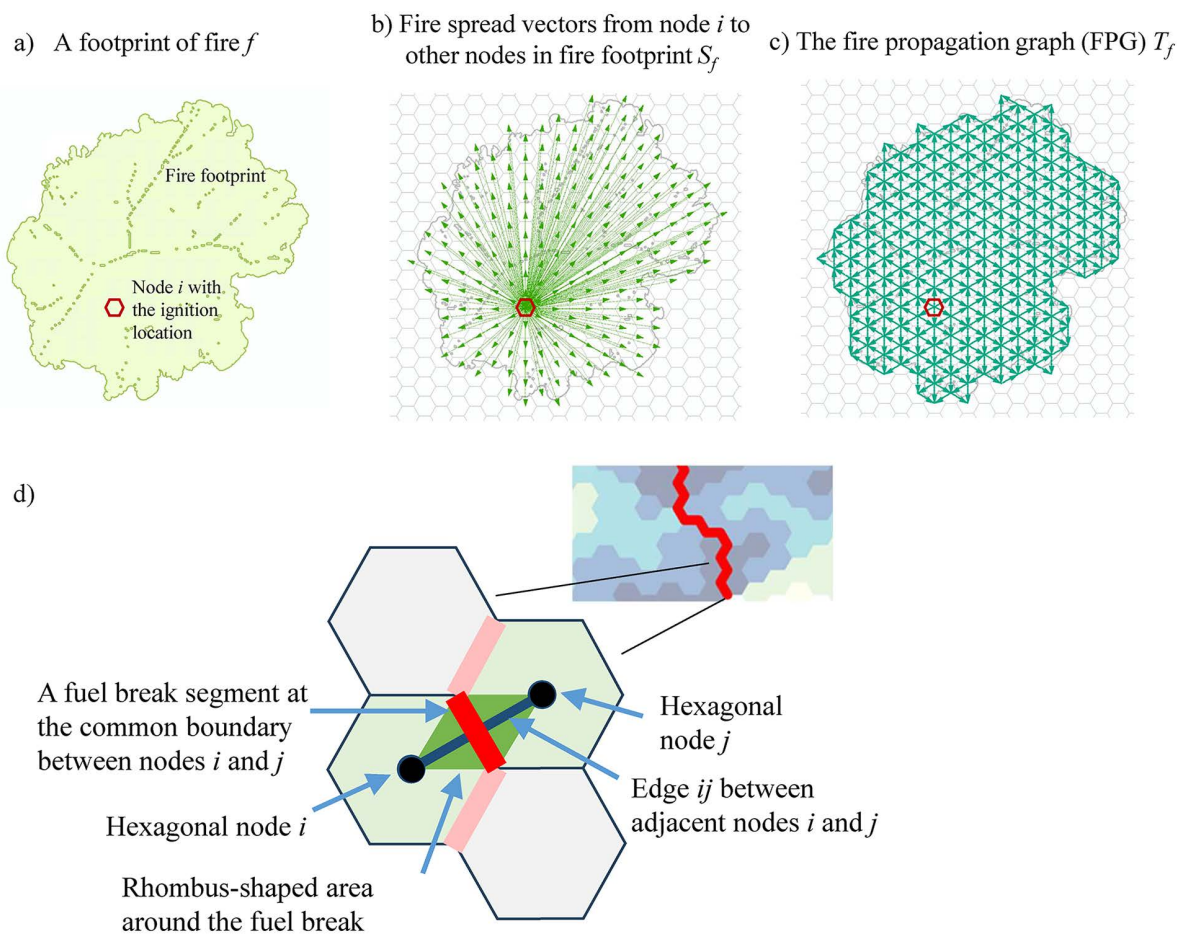


Fig 4. A fire footprint and a fire propagation graph (FPG): a) a simulated fire footprint and the ignition node i ; b) a landscape depicted as a hexagonal node network G with binary fire spread vectors from the ignition node; c) an FPG with the possibility of fire spread to a node from all adjacent upstream nodes; d) depiction of a fuel break segment across an edge ij in a network setting.

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the burn intensity estimates based on the configuration of fuel types, topography, weather and wind, so the resulting burn intensity pattern within each fire footprint was impacted by all these factors.

For each footprint S_f we composed the fire propagation graph (FPG) T_f —a directed acyclic graph with the root node ϕ_f including the fire's ignition location and directed edges ij connecting adjacent nodes i and j , $(i,j) \in S_f$ depicting the possible fire propagation paths within the fire's footprint S_f (Fig 4C). We assumed that fire f could spread to node j from all adjacent upstream nodes i within the fire footprint S_f such that node j in the FPG T_f is connected to all upstream nodes i . Note that some fire growth models, such as Cell2Fire [60], can generate tree-like graphs that depict the fire propagation to a node from one upstream node only (Fig 1A). Since our study applied the FPGs in the broader context of uncertain high-severity crown fires, where firebrand spotting may create multiple fire spread paths from/to adjacent locations, the FPG must incorporate the uncertain potential of spotting. We depicted the spotting potential in the FPGs by including all plausible ways that a fire could propagate between adjacent upstream and downstream nodes (Fig 1D). This topology better characterizes the uncertainty of local fire behaviour in boreal forests of North America, where crown fires may simultaneously spread from/to multiple directions due to rapid changes of weather, which may occur within hours [26,77,78].

2.3.1. Minimizing the total burn area in the FPG set. Consider a fire f with a footprint S_f and the corresponding FPG graph T_f . The fire propagation flow starts at the ignition node ϕ_f to other nodes through the directed edges ij comprising the elements of T_f . Without fuel breaks, the fire is expected to propagate through all edges ij in T_f ($ij \in T_f$). A collection of fuel breaks, if allocated within the fire's footprint S_f , may stop the spread of fire f through some portions of the FPG and reduce the burned area of fire f from S_f to S'_f (Fig 1B and 1D). The burned portion of fire f that persists after allocating the fuel breaks can be found by tracing the fire propagation flow from the ignition node ϕ_f through the edges ij in T_f that are not blocked by the fuel breaks.

Fires may burn with different intensities, and a decision-maker may choose among different fuel break widths (or types) depending on the anticipated burn conditions in the candidate sites for protection and the available budget. We introduce a set G of possible fuel break types g , $g = 1, 2, \dots, |G|$, where each type g is characterized by a fuel break width that defines the maximum firebrand spotting distance that this fuel break type can contain in location i . Spotting caused by high-intensity fires is a critical factor of large fire spread [82,83], hence we needed a binary parameter χ_{fig} to specify whether the width of fuel break type g is sufficient to contain fire f that burns in node i with intensity level β_{fi} ($\chi_{fig} = 1$ and $\chi_{fig} = 0$ otherwise). For this study, we derived χ_{fig} as follows. We used the local burn intensity level of fire f in node i , β_{fi} (which we generated with the spatial fire growth model), to calculate the maximum firebrand spotting distance for that intensity level using the spotting models of Albini et al. [82], Chase [84] and Thompson et al. [26] (see S2 Appendix). A fuel break type g is expected to contain the spread of fire f through node i (i.e., $\chi_{fig} = 1$) if its width is greater than the maximum spotting distance predicted by the spotting model for that location based on the burn intensity level β_{fi} .

The fuel breaks are modelled as the removal of edges between adjacent nodes in landscape N . The binary variable y_{ijg} indicates whether a fuel break type g is allocated across edge ij between adjacent nodes i and j , $ij \in E$ ($y_{ijg} = 1$, and $y_{ijg} = 0$ otherwise) (Fig 4D). The vicinity area around the removed edge ij where a fuel break segment could be placed is perhaps most easily conceptualized as a rhombus with its longest diagonal equivalent to the edge length between adjacent nodes and shortest diagonal equal to the length of the common boundary between these nodes (Fig 4D). The removal of edge ij is analogous to placing a fuel break segment near the common boundary between nodes i and j (Fig 4Dd). Compared to the depiction of fuel breaks as the removal of nodes – where the fuel break area is defined by the node size [42,47] – the removal of edges enables the selection of a variable fuel break width along the edge between adjacent nodes. The condition when fuel break type g can contain the spread of fire f between nodes i and j can be written as $y_{ijg}\chi_{fig}\chi_{fjg} = 1$.

In our formulation, a fire is allowed to propagate to node i from all upstream adjacent nodes in FPG T_f (Fig 1C). The binary decision variable n_{fi} defines the burned status of node i in FTG T_f after fuel break placement ($n_{fi} = 1$ when fire f spreads to i from the ignition node ϕ_f). For equal-area nodes i such as those used in this study, the remaining unburned area of fire footprint f after fuel break placement is equivalent to $S'_f = \sum n_{fi}$.

The FPGs T_f in fire scenario set F depict the discrete realizations of the uncertain fire regime where each realization f occurs with the probability $1/|F|$. Using this setting, we formulate a fuel break allocation problem that minimizes the sum of the remaining burned portions of fire footprints S'_f (and corresponding FPGs T_f) over F scenarios in landscape N after allocating the fuel breaks (problem 1 hereafter). Table 2 lists the model equations. Since all fire scenarios f have equal probability of occurrence, minimizing the problem 1 objective (1) is equivalent to minimizing the expected burn area in landscape N . Problem 1 also includes a set of constraints (7) (Eqs.S1.1-S1.3 S1 Appendix) that prevent the creation of loops and clusters, so the fuel breaks appear as linear segments.

Problem 1 minimizes the expected burn area in $|F|$ fire scenarios without penalizing for fuel break failures in some scenarios. In an operational context, high-intensity fires always pose a greater threat than low-intensity fires because of their higher propensity for firebrand production and transport [19] and lower chances of successful containment [85]. A practical fire mitigation plan may include a desired threshold of successful fire containment. Our fuel break allocation problem 2 is based on problem 1 formulation (Eqs.1-7 in Table 2) but adds the constraint (8) that establishes a maximum 5% whole-landscape failure limit for the allocated fuel breaks in landscape N . This

Table 2. Problem 1-6 formulation. (See Table 1 for definitions of symbolic notations).

Model equation		Description
Problem 1:		
$\min \sum_{f \in F} \sum_{i \in S_f} n_{fi}$	(1)	Minimize the total burn area over F fire scenarios.
Subject to:		
$\sum_{(i,j) \in E} \sum_{g \in G} y_{ijg} c_{ijg} \leq B$	(2)	Budget constraint defining the maximum allowed fuel break area B . Parameter c_{ij} defines the area of a fuel break type g along edge ij (see Fig 4d).
$n_{fi} = 1 \forall i \in S_f, f \in F, i \in \varphi_f$	(3)	Node i with the ignition location for fire f receives burned status $n_{fi} = 1$ $i \in \varphi_f$ and starts the fire propagation in FPG T_f .
$y_{ijg} = y_{jig} \forall (i,j) \in E, i \neq j, g \in G$	(4)	The removal of edges between nodes i and j occurs in both directions when a fuel break is placed between i and j .
$\sum_{g \in G} y_{ijg} \leq 1 \forall (i,j) \in E, i \neq j$	(5)	No more than one fuel break type g can be allocated to edge ij .
$\theta_{fj} n_{fj} \geq \sum_{i \in S_f \cap (i,j) \in T_f} (n_{fi} - \sum_{g \in G} y_{ijg} \chi_{fig} \chi_{fjg}) \forall j \in S_f, f \in F$	(6)	Fire f cannot spread to node j through FPG T_f if all edges $ij, (ij) \in T_f$ connecting adjacent upstream nodes i with burned status $n_{fi} = 1$ to j have fuel breaks installed (so $y_{ijg} = 1$). θ_{fj} defines the number of adjacent upstream nodes i connected to node j . An allocation of fuel break type g in arc ij in fire scenario f resets the status of an incoming fire from node i to node j (defined by $n_{fi} = 1$) to zero if the width of fuel break g is sufficient to stop the fire's spread from i to j . The burned status variable n_{fj} in node j becomes one if one or more edges ij do not have fuel breaks or their width is insufficient to stop the fire's spread from i to j .
Allocate the fuel breaks as linear segments, no loops	(7)	Defined by constraints (S1.1-S1.3) in S1 Appendix.
Problem 2:		
Minimize objective function (1)	(1)	Minimize the total burn area over F fire scenarios.
Subject to: constraints (2–7) and	(2–7)	(see problem 1 formulation)
$\sum_{f \in F} \sum_{(i,j) \in T_f} \sum_{g \in G} [y_{ijg} (1 - \chi_{fig} \chi_{fjg})] \leq 0.05 \sum_{f \in F} \sum_{(i,j) \in T_f} \sum_{g \in G} y_{ijg}$	(8)	Specifies a maximum 5% failure limit for the allocated fuel breaks in landscape N . Term $1 - \chi_{fig} \chi_{fjg} = 1$ when fuel break g fails to stop the propagation of fire f from node i to node j .
Problem 3:		
$\min \frac{1}{ F (1-\alpha)} \sum_{f \in F} \mu_f + Z$	(9)	Minimize the Conditional Value-at-Risk (CVaR) of the burn area.
Subject to: constraints (2–7) and	(2–7)	(see problem 1 formulation)
$\mu_f \geq \sum_{i \in S_f} n_{fi} - Z \forall f \in F$	(10)	The calculation of an auxiliary decision variable μ_f to linearize the minimization of Conditional Value-at-Risk (CVaR).
Problem 4:		
Minimize objective function (9)	(9)	Minimize the Conditional Value-at-Risk (CVaR) of the burn area.
Subject to: constraints (2–8,10)	(2-8, 10)	(see problem 1 and 2 formulations)
Problem 5:		
$\min \sum_{i \in N} \sum_{j \in \Omega_i} u_{ij}$	(11)	Minimize the number of node pairs ij between which fire spread is possible in one or more fire scenarios f .
Subject to: constraints (2–7)	(2–7)	(see problem 1 formulation)
$u_{ij} N \geq \sum_{f \in F_i} n_{fj} \forall i \in N, j \in \Omega_i, i \neq j$	(12)	Estimates the value of the binary variable u_{ij} which becomes one if a fire can spread from an ignition node i to a destination node j in one or more fire scenarios f .

(Continued)

Table 2. (Continued)

Model equation		Description
Problem 6:		
Minimize objective function (11)	(11)	Minimize the number of node pairs ij between which fire spread is possible in one or more fire scenarios f .
Subject to: constraints (2–8,12)	(2-8, 12)	(see problem 1 and 5 formulations)

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limit defines the fire containment probability at the whole-landscape level. It does not enforce the failure threshold for each allocated fuel break segment in the area. In practice, adding a constraint enforcing the 5% failure limit for each fuel break segment would make the solutions more conservative because it would restrict the flexibility to readjust the segment-level fuel break effectiveness while attempting to meet the whole-landscape containment target. Since our application aimed to reduce the wildfire risk across the entire landscape, the use of a whole-landscape threshold felt justified.

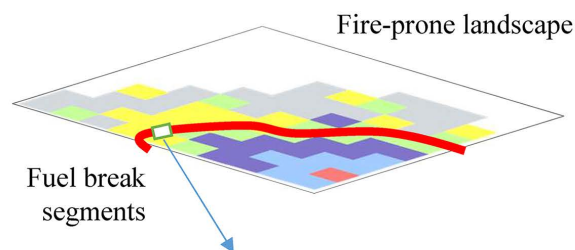
Problem 2 prioritizes the reduction of the burned area that may be caused by high-intensity fires and maximizes the capacity of the fuel breaks to stop almost all fires, including those of high severity.

2.3.2. Minimizing the expected worst burn area. In our problem 1, the uncertainty about which patches might get burned after allocating the fuel breaks is characterized by the distribution of the remaining burned portions of the FPGs over $|F|$ fire scenarios. Minimizing the mean value of that distribution does not guarantee the reduction of the area burned by the largest, most catastrophic fires. Since fire sizes in boreal regions generally follow a power law distribution where small fires dominate [86,87], the largest fires are rare and therefore contribute only modestly to the average burn area over $|F|$ scenarios in objective (1), although their impacts can be disproportionately large in the context of individual scenarios [88,89]. As a practical matter, very large values in the right-hand tail of the burned area distribution may indicate failure to contain the spread of these more destructive fires, which translates to greater damage and higher fire response costs.

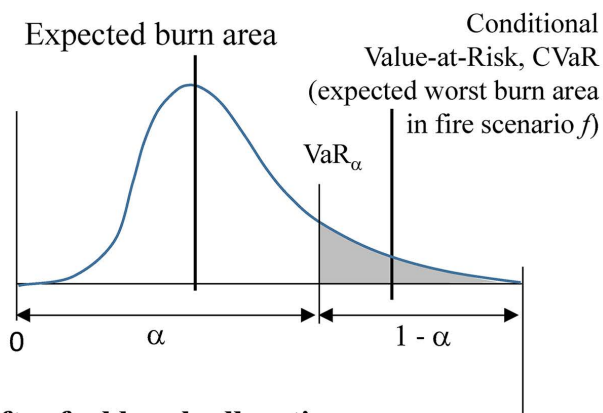
When faced with potential failures of the fuel breaks to stop high-intensity fires, a risk-averse decision-maker may consider such failures unacceptable and so will try to minimize these outcomes at all costs. This is an example of tail risk-averse behaviour [90]. A risk-averse decision-maker evaluates potential actions in terms of the minimum utility that might emerge from selecting these actions. If confidence about estimating the potential fire spread outcomes is poor, a tail risk-averse strategy is to prioritize the best of the expected worst outcomes.

Minimizing the expected worst burn area requires minimizing the expected value of the right tail of the distribution of the burn area across $|F|$ scenarios. This can be achieved by minimizing an upper-percentile-based metric, such as Conditional Value-at-Risk (CVaR) [91–93]. In our case, CVaR for a confidence level α , $\alpha \in [0;1]$, can be defined as the expected burn area after fuel break placement over the $(1-\alpha) \times 100\%$ worst scenarios (Fig 5). For a random variable, CVaR_α is the conditional mean of the values (i.e., the remaining burn area after fuel break placement, Σn_{ij}) exceeding VaR_α , which is the value in the distribution of burn areas that is exceeded only in $(1-\alpha) \times 100\%$ of the scenarios. We set the α level to 0.95. This level represents the point when the size of an upper tail of the fire size distribution is sufficient to track the most threatening large fire events without making it too sensitive to the occurrence of the extreme cases in a discrete set F of simulated fire scenarios (see S1 Appendix).

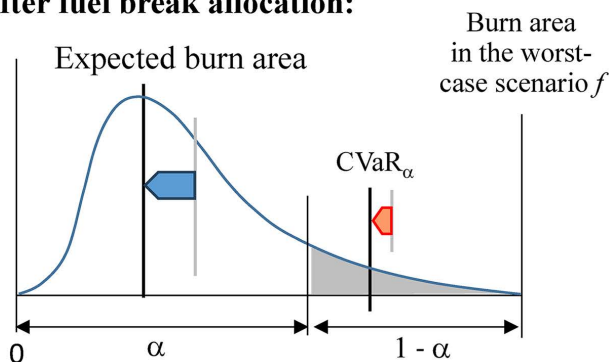
The CVaR is convex with respect to the decision variables [92,93]. For discrete scenario-based distributions such as our problems 1 and 2, minimizing CVaR can be expressed by a set of linear equations [92]. Analogously to Vilches et al. [64], our problem 3 depicts the tail risk-averse strategy of avoiding the expected worst-case burn outcomes by minimizing the CVaR of the burn area. For a distribution of $|F|$ scenarios with occurrence probabilities $1/|F|$, problem 3 with CVaR_α



Before fuel break allocation:



After fuel break allocation:



Distribution of burn areas across F fire scenarios

Problem objective:

-  Minimize the expected burn area – problems 1,2
-  Minimize the expected worst burn area – problems 3,4

Fig 5. The Conditional Value-at-Risk (CVaR) concept.

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minimization is approximated with the objective function (9) and equivalent sets of $|F| + 1$ auxiliary decision variables and $|F| + 1$ inequality constraints (10) (Table 2). The objective (9) minimizes the expected worst burned area over $|F|$ fire scenarios after allocating the fuel breaks. Term $\sum_{i \in S_f} n_{fi}$ in constraint (10) in Table 2 defines the burned area after fuel break placement in fire scenario f , and symbols Z and μ_f define the auxiliary decision variables.

Problem 4 that minimizes the expected worst-case burn area with a 5% fuel break failure limit is formulated analogously to problem 3 but with added constraint (10).

2.3.3. Minimizing the fire spread connectivity. An alternative approach to reduce wildfire hazard is to reduce the connectivity between patches with fuel by minimizing the total number of node pairs between which fire spread is possible. For each node pair ij in landscape N , one must estimate whether the allocated fuel breaks could disrupt fire propagation from node i to node j in one or more fire scenarios f . Previously, the allocation of fuel treatments to minimize fuel connectivity was solved as a critical node detection problem [46–48], which finds the key nodes in a fuel network whose removal maximally degrades its connectivity. However, this formulation did not permit selection of alternative fuel break types, nor did it account for potential fuel break failures. We addressed this shortcoming with our planning problem 5 whose objective minimizes the number of node pairs between which fire spread is possible in one or more fire scenarios f (Table 2). For each pair of ignition node i and destination node j in landscape N , the binary decision variable u_{ij} in objective (11) in Table 2 specifies whether a fire could spread from i to j in one or more fire scenarios f (i.e., $u_{ij} = 1$). For each node i , set Ω_i in Equations (11,12) defines a *fireplain* that delineates the area where wildfires could spread from i during a designated timespan (cf. [94]) (Fig 6). The right side of Equation (12) denotes the sum of the burn status variables n_{ij} at destination node j for all fires f that were ignited in origin node i and able to spread to node j . Set F_i in Eq. (12) includes the fires f with their ignition locations in node i . The right side of Equation (12) becomes positive if there is a connecting flow path from node i to node j through the FPGs in one or more fire scenarios f after the allocation of fuel breaks.

Problem 6, which minimizes the number of node pairs with possible fire spread under a 5% fuel break failure limit, is formulated analogously to problem 5 but with added constraint (8). Table 3 lists the model scenarios.

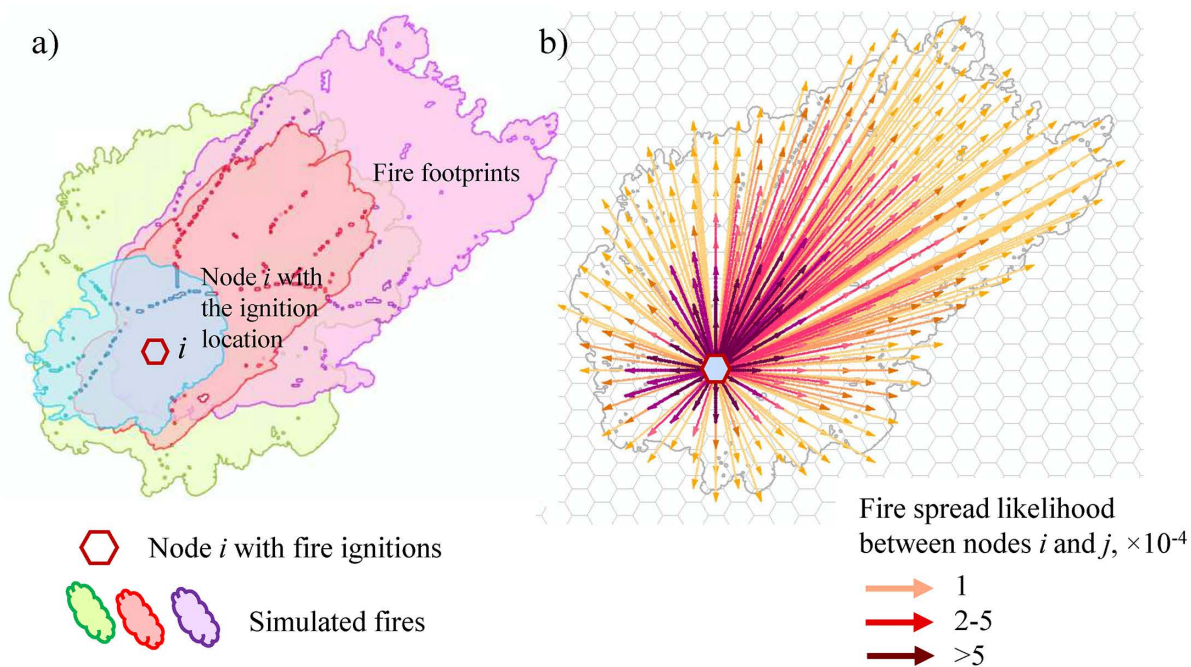


Fig 6. Delineating a fireplain around node i : a) simulated wildfire footprints with their ignition locations in node i ; b) delineating the fireplain Ω_i around node i based on these footprints.

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Table 3. Model scenarios.

Performance metric in the objective function	Objective function equation*	Whole-landscape fuel break failure rate limit	
		No limit	5% limit
Min [total burn area] over $ F $ fire scenarios	$\min \sum_{f \in F} \sum_{i \in S_f} n_{fi}$	Problem 1	Problem 2
Min [expected worst burn area] over $ F $ scenarios	$\min \frac{1}{ F (1-\alpha)} \sum_{f \in F} \mu_f + Z$	Problem 3	Problem 4
Min [number of node pairs with possible fire spread]	$\sum_{i \in N} \sum_{j \in \Omega_i} u_{ij}$	Problem 5	Problem 6

* See Table 1 for symbolic notations and Table 2 for the model equation listing.

<https://doi.org/10.1371/journal.pcsy.0000117.t003>

2.4. Protecting the wildlife migration routes in the fire mitigation scenarios

Forest landscapes may include critical corridors which are used by wildlife (such as caribou) as a part of their seasonal behaviour [95]. Mapping the movements of these animals through a landscape is done by tracking a sample of GPS-collared individuals. Their movements are depicted as a collection of paths crossing the landscape, with migratory movements being represented by the long path lengths [95,96]. For this case study, we used GPS collars on 189 caribou collared between 1998 and 2016 from the Red Rock-Prairie Creek and Narraway caribou herds to identify a set of migration routes that overlap our study area. We have converted GPS relocations to connected paths and removed the paths with missing data which produced unrealistically long paths. We extracted the start and end points of the top 1% longest path segments and converted them to straight line features which yielded 422 straight line features from 155 caribou individuals. We only used the resulting migration routes that overlapped our study area, as such, most routes came from the Red Rock-Prairie Creek data. We then subset the resulting line features most frequently aligned with the northeast-southwest directions connecting the winter and summer ranges of the two herds. Using these we defined a set R of caribou migration routes $r, r \in R$, each representing a segmented path digitized from caribou movement data at the spatial resolution of network nodes i (Fig 7C). A path r can overlap one or more nodes i and is characterized by length ρ_r , measured as the total number of nodes i it overlaps. The path length ρ_r serves as a path conservation priority measure, with the longest paths receiving the highest priority.

A binary parameter, σ_{rij} , indicates whether path r overlaps the area around edge ij in landscape N where a fuel break segment may be established ($\sigma_{rij} = 1$ when path r intersects either node i or j or both). We assume that an overlap occurs when path r crosses any part of nodes i or j . This assumption accounts for the distance (at least 500 m) at which the negative impact of disturbances on caribou populations remains significant [97,98].

The allocation of fuel breaks is often most effective in regions with large amounts of old coniferous forest, which tends to be highly flammable. In our study area, these conifer forests also have good capacity to support caribou populations, so there is a trade-off between minimizing the fire spread potential in areas with conifer stands vs. protecting as many caribou migrations routes in those areas as possible. Since the fuel breaks had to be wide (i.e., ≥ 360 m) to be effective in the presence of firebrand spotting, the creation of such large disturbance spaces would significantly disrupt caribou movement behavior. We treated the disruptions as binary events and introduced a binary variable, q_r , that tracks whether caribou path r crosses one or more areas near edges ij with allocated fuel breaks. For caribou path r , constraint (13) specifies $q_r = 1$ when the path is fragmented by fuel breaks and constraint (14) specifies $q_r = 0$ when r has no intersecting fuel breaks, i.e.,:

$$q_r \sum_{i \neq j} \sigma_{rij} \geq \sum_{i \neq j} \sigma_{rij} \sum_{g \in G} y_{ijg} \quad \forall r \in R \quad (13)$$

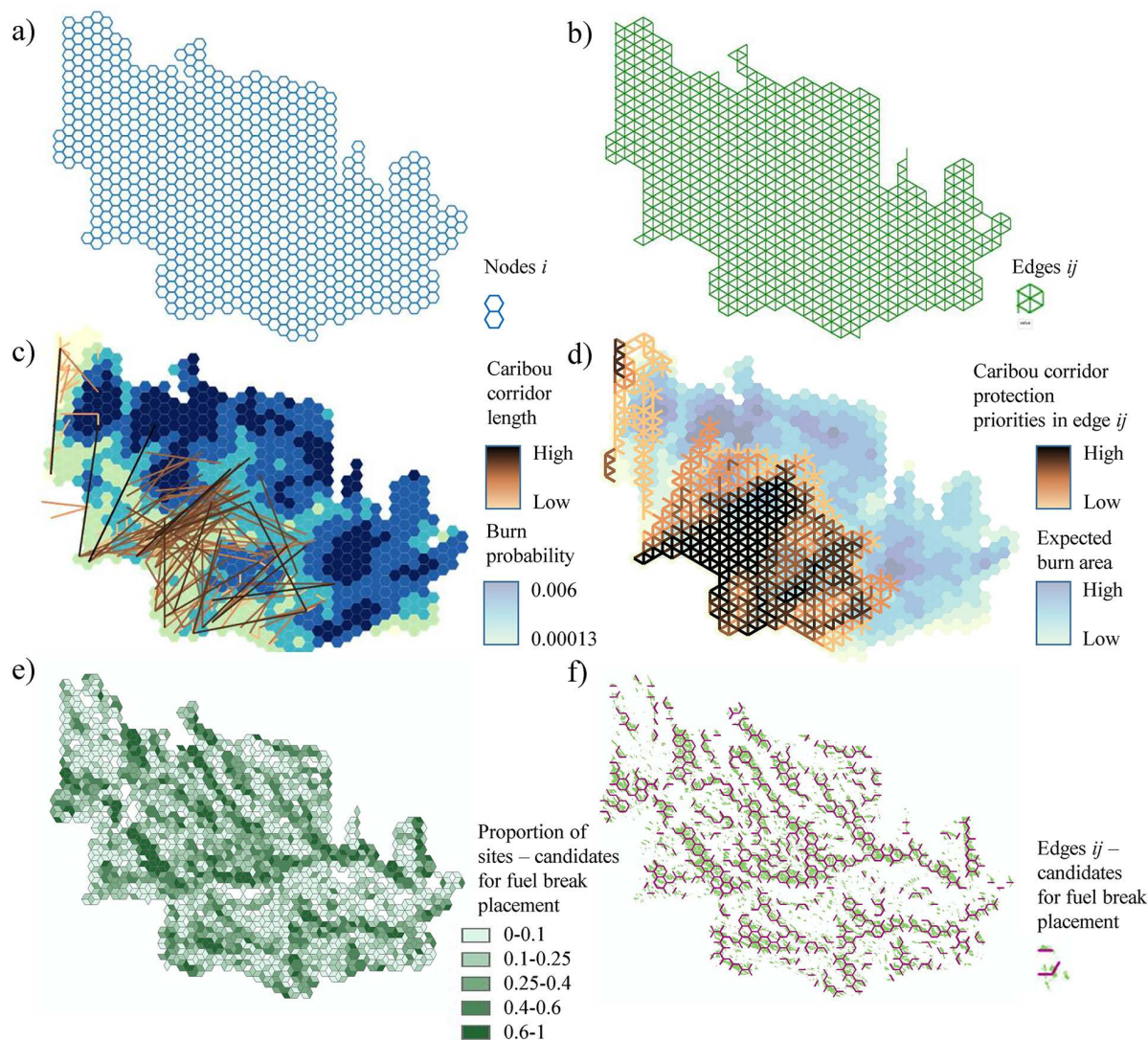


Fig 7. Landscape network: a) nodes i ; b) edges ij ; c) caribou migration routes. Background map shows the burn probability; d) caribou migration route protection priorities for edges ij . Background map shows the expected burn area; e) proportion of each node with west-, south- and southwest-facing slopes facing the prevailing winds, used to identify suitable sites for fuel break placement; f) edges ij representing potential candidates for fuel break placement. The map data can be found in [S4 Appendix](#). Mapping software used: Python Matplotlib 3.4.

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$$q_r \leq \sum_{i \neq j}^{(i,j) \in E} \sigma_{rij} \sum_{g \in G} y_{ijg} \forall r \in R \quad (14)$$

A decision-maker defines the maximum proportion of the caribou migration routes, $q_{\max}$ that can be intersected by fuel breaks. Constraint (15) ensures that the proportion of the caribou paths disrupted by the fuel breaks does not exceed $q_{\max}$, i.e.,:

$$\sum_{r \in R} \rho_r q_r \leq q_{\max} \sum_{r \in R} \rho_r \quad (15)$$

2.5. Building fire propagation graphs from wildfire simulation data

We defined the fuel breaks (i.e., strategic fuel barriers) as spatial units with removed or substantially reduced forest fuel that can be established as a part of standard forestry operations and whose size would be compatible with the size of large clearcuts. We set the node size in fuel network N depicting the study area to 400 ha, which was sufficient to track major fire behaviour patterns and the caribou migration routes in the area. This node size limited the maximum fuel break width that could be evaluated in problems 1–6 to the cross-sectional width of a node (2.15 km), which is equivalent to the length of edge ij between a node i and an adjacent node j (see Fig 4D). We adopted a large node size to account for the possibility of spotting caused by high-intensity fires under extreme weather [99]. Ideally, a fuel break should be of sufficient width to contain potential spotting for most predicted fires. Using the maximum spotting distance models of Albini et al. [82], we estimated that a 2.15-km node cross-section would exceed the estimated maximum spotting distances for 99.5% of the predicted fires in the study area with fire line intensities up to 70,000 kW/m; fuel break widths below this 2.15-km maximum would be expected to contain a progressively smaller subset of predicted fires. Thus, our assessment of fuel break effectiveness was based on a relatively conservative underlying assumption. Since our fuel break planning was intended to assist with strategic mitigation of wildfire risk, having wide fuel breaks was deemed important for our study area because – due to its remote location – fire crews’ response times are expected to be long, especially during the peak fire season. This conservative approach is also consistent with regional management decisions, presented in the draft Upper Smoky Sub-Regional Plan [100], that anticipate the creation of wide strategic fire barriers in the area. Within each simulated fuel break, less flammable fuels, such as broadleaf trees and more open vegetation were assumed, which allows for standard fire suppression activities using fixed-wind air tankers [85] that are commonly used in fire suppression in Alberta.

We built the fire propagation graphs T_f using ignition locations and fire footprints S_f simulated for the study area (see S1 Appendix for the procedure of composing the FPGs). Parts of the study area with proportions of south-, west- and southwest-facing slopes (i.e., that face the prevailing winds) equal to 20% or higher were set as suitable candidates for fuel break placement (Fig 7E and 7F). We considered five fuel break types g with corresponding widths of 0.36, 0.67, 1.1, 1.55 and 2.15 km. For each fuel break type g , we calculated the maximum burn intensity level this fuel break type could potentially contain using the spotting distance model of Albini et al. [82] (see S2 Appendix).

The maximum corresponding fire intensity levels in node i that could be contained by the fuel break types g were estimated as 3500, 6500, 15000, 32000 and 70500 kW-m⁻¹, respectively. For each node i in fire footprint S_f , we set the values of the parameter χ_{fig} – which specified whether fuel break type g could stop fire f in node i – by comparing the burn intensity levels β_{fi} estimated with the fire growth model in i with the corresponding intensity threshold values calculated with the spotting distance model for a particular width of fuel break type g . S1 Appendix provides the model solution procedure.

3. Results

3.1. Mapping the fuel break solutions

The fuel network comprising the study area included 834 nodes and 4788 edges (Fig 7A and 7B). The area is dominated by mature conifer forests and, as noted earlier, is highly susceptible to fires driven by prevailing winds from west-southwest (Fig 3A). The fire spread directions and the footprints of the simulated wildfires were influenced by the prevailing wind pattern (Fig 3B), with 95% of fires expected to spread over distances of 12.9 km or less. The northern and eastern portions of the study area located at lower elevations are characterized by warmer weather, the occurrence of

both human-caused and lighting-caused fires and higher projected burn risk than the areas located at higher elevations in the southwestern region of the area ([Fig 7C](#)), which tend to experience colder weather and mostly lighting-caused fires.

The maps in [Figs 8](#) and [9](#) show the fuel break solutions for the fuel break areas of 100 and 150 km². The background maps in [Figs 8](#) and [9](#) indicate the expected burn area in node *i* after fuel break placement. The fuel breaks tended to be allocated as linear segments that were roughly perpendicular to the directions of the prevailing winds ([Fig 3A](#)).

3.2. Minimizing the expected burn area vs. fuel connectivity

Problem 1 solutions, which minimized the expected burn area, generally segmented the landscape by means of moderate-length fuel breaks ([Figs 8A](#) and [9A](#)). In conditions with a strong directional wind pattern such as in our study (see [Fig 3A](#)), the impacts of fuel breaks are likely to have limited depth. In our case, the most feasible strategy is to segment the forest landscape by evenly spaced fuel breaks oriented perpendicularly to the prevailing winds. The fuel breaks were rarely placed in high-elevation areas in the southwestern portion of the landscape where colder weather is less conducive to the spread of large fires than in the low-elevation areas. To maximize the total length of the allocated fuel breaks, problem 1 tended to allocate lowest-width (360 m) fuel breaks ([Figs 8A](#) and [9A](#)), which resulted in a high (30.9–35.6%) fuel break failure rate ([Table 4](#), [Fig 10](#)). (See [Figs S3.1](#) and [S3.2](#) in [S3 Appendix](#) depicting the fuel break failure rates as pink haloes around the allocated segments). The high failure rate stems from the formulation of the problem 1 objective, which minimizes the expected burn area over *F* fire scenarios but does not minimize the burn area of the largest or most intense fires. Nevertheless, a policy of maximizing the total fuel break length at the cost of their lower overall effectiveness is feasible for the study area, because the predicted fire size distribution is dominated by small, moderate-severity fires (which could be contained by moderate-width fuel breaks) ([Figs 8A](#) and [9A](#)).

Adding the 5% fuel break failure threshold in problem 2 solutions created wider fuel breaks ([Table 4](#)) aimed at containing most of the high-severity fires in the landscape driven by spotting ([Figs 8B](#) and [9B](#)). Most fuel breaks were positioned in low-elevation regions, and the total fuel break length was shorter than in problem 1 solutions ([Figs 8B](#) and [9B](#) vs. [Figs 8A](#) and [9A](#)).

In problem 3 solutions, which minimized the expected worst burn area, some fuel breaks were allocated in high-elevation regions with lower fire hazard ([Figs 8C](#) and [9C](#)). Because the chance of large fire occurrence, while rare, existed across the study area, the allocation of fuel breaks was more diffuse than in problem 1 solutions. The average fuel break failure rate was lower than the failure rate in problem 1 solutions but still within the 25.9–33.5% range ([Table 4](#)). Note that problem 3 aimed to reduce the fire hazard in only those scenarios with the largest burn areas. Since the fire distribution in the area was dominated by small fires, minimizing the occurrence of only the largest fires targeted a limited subset of the potential fires in the area, which explains the poorer combined performance of problem 3 solutions versus problem 1 solutions ([Table 4](#)).

Adding the 5% fuel break failure threshold in problem 4 solutions resulted in fuel break allocations similar to problem 2 solutions ([Figs 8D](#) and [9D](#), [Table 4](#)). Typically, the allocated fuel breaks were wider than in problem 3 solutions, in some cases at the maximum node width of 2.15 km.

In problem 5 solutions that minimized fuel connectivity, the fuel breaks were allocated in longer segments aimed to partition the landscape ([Figs 8E](#) and [9E](#)). Problem 5 solutions had a lower fuel break failure rate than problems 1 and 3 solutions ([Table 4](#)). Adding the 5% fuel break failure limit in problem 6 solutions resulted in a fuel break pattern that resembled problems 2 and 4 solutions; however, the fuel breaks were arranged in fewer but longer segments. Most of the fuel breaks were allocated in segments 1.1 km to 1.55 km wide ([Table 4](#)).

3.3. Fuel break performance vs. the allocated treatment area

As the total fuel break area increased, the optimal solutions increasingly segmented the landscape into partial compartments ([Figs 8](#) and [9](#)). In problems 1, 3 and 5 without the fuel break failure threshold, reducing the expected burn area

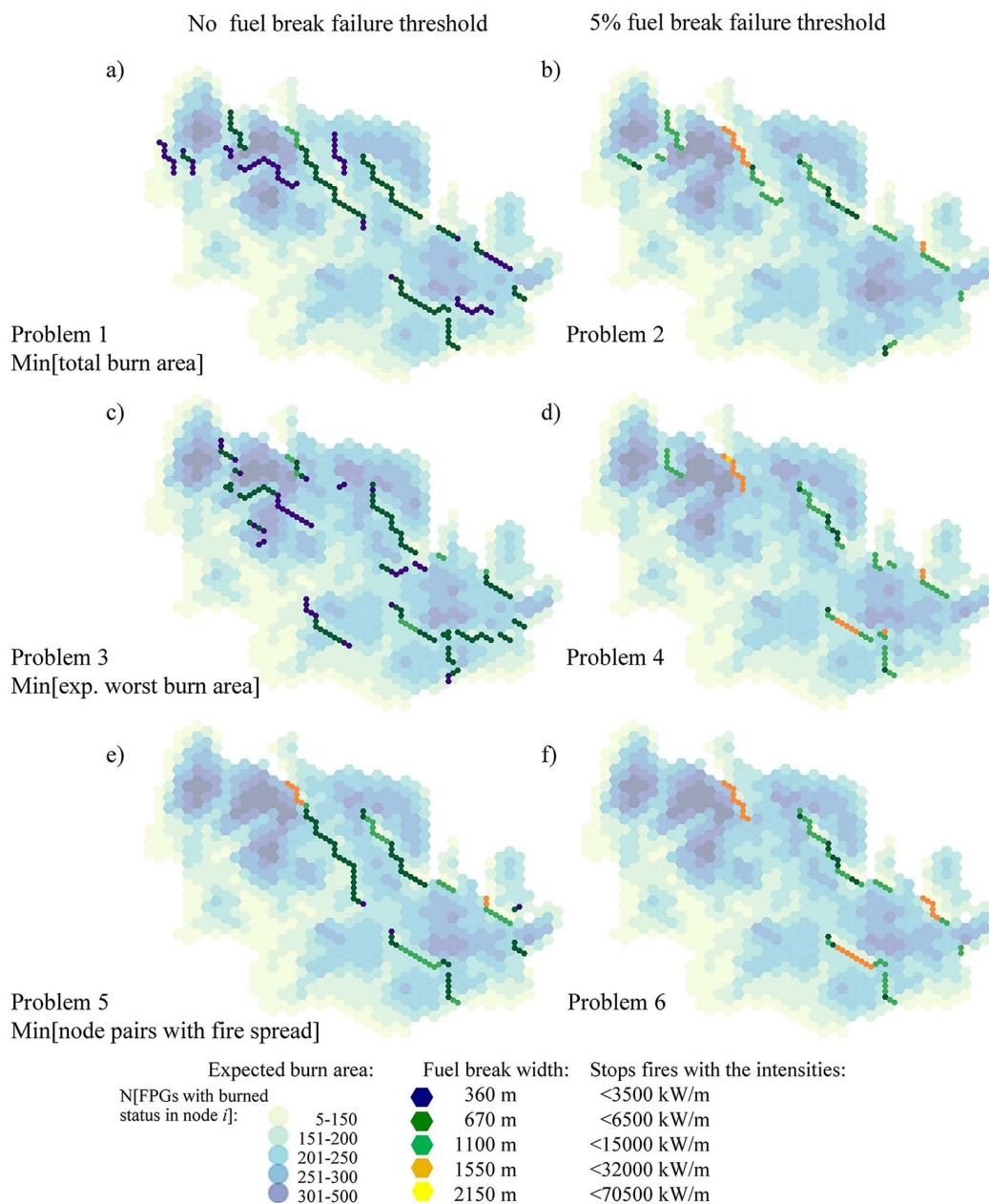


Fig 8. Fuel break allocation solutions for the total fuel break area $B = 100 \text{ km}^2$. The background maps show the number of FPGs with burned status after fuel break allocation. The 5% fuel break failure threshold is applied at the whole-landscape level. The map data can be found in [S4 Appendix](#). Mapping software used: Python Matplotlib 3.4.

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and fire spread connectivity followed the rule of diminishing returns (Figs 10A, 10C and 10E): larger-budget solutions had lower marginal effectiveness. Problem 1, 3 and 5 solutions performed differently in dimensions of the expected burn area and the fire spread potential. Problem 5 solutions achieved the most effective reduction of the fire spread potential across all budget levels (Fig 10E), whereas problem 1 solutions were the most effective in reducing the expected burn area (Fig 10A). Problems 1, 3 and 5 performed similarly in reducing the expected worst burn area (Fig 10C). Problems 2,

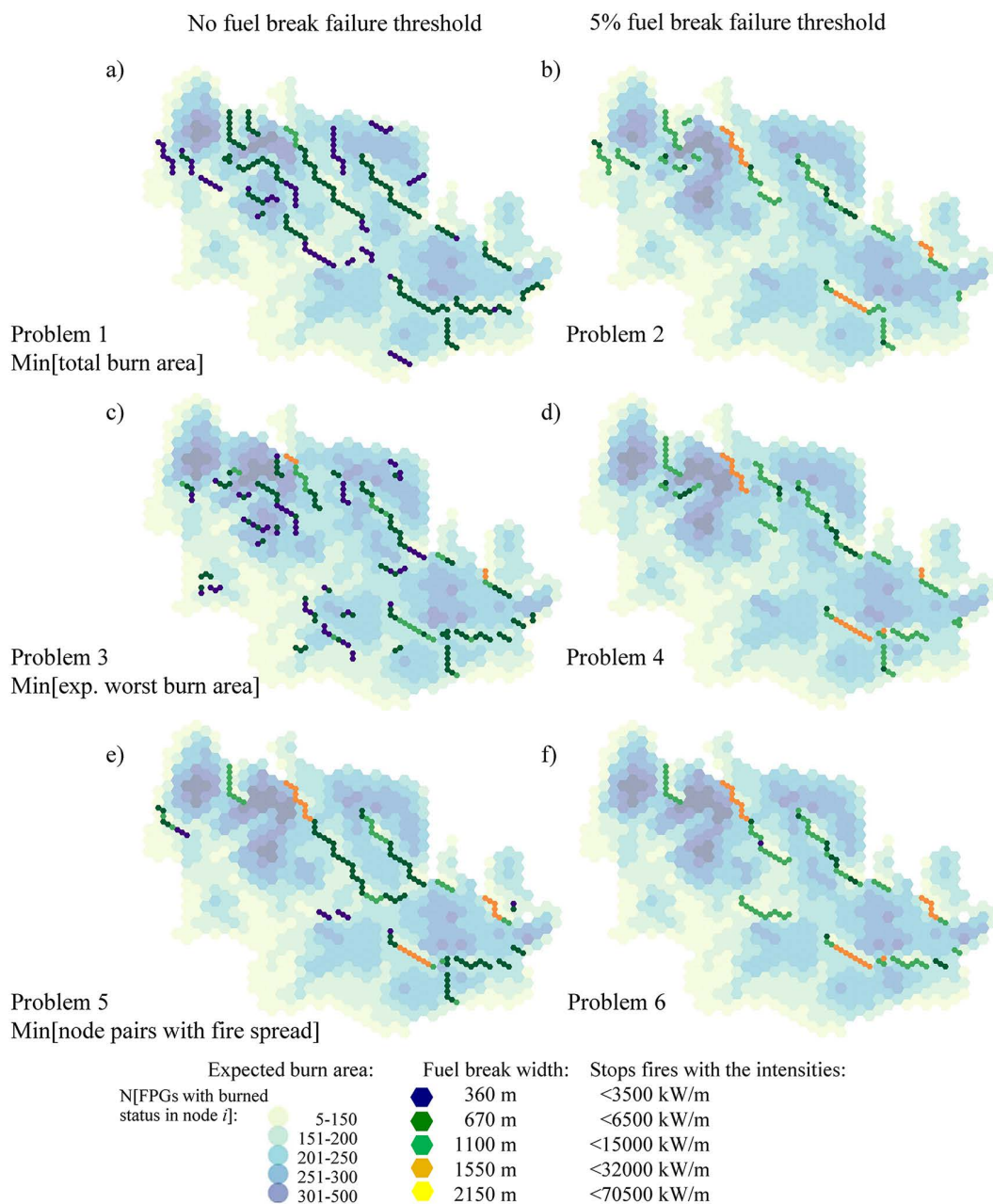


Fig 9. Fuel break allocation solutions for the total fuel break area $B = 150 \text{ km}^2$. The background maps show the number of FPGs with burned status after fuel break allocation. The 5% fuel break failure threshold is applied at the whole-landscape level. The map data can be found in [S4 Appendix](#). Mapping software used: Python Matplotlib 3.4.

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4 and 6 with the 5% fuel break failure threshold were unable to reduce the expected burn area as effectively as problem 1 solutions (Fig 10B), but their capacity to reduce the wildfire spread connectivity was close to problem 5 solutions without the fuel break failure limit (Fig 5F). Problem 3 that minimized the expected worst burn area performed closely to problems 2, 4 and 6 (Fig 10D).

Table 4. Fuel break allocation summaries in problems 1-6 optimal solutions.

Total fuel break area, <i>B</i>	Fuel break failure rate, %	Problem type (see Table 2)	Exp. burn area (problem 1 objective) vs. the no-treatment scenario*	Exp. worst burn area (problem 3) vs. the no-treatment scenario*	N[node pairs with fire spread] (problem 5 objective) vs. the no-treatment scenario*	Budget portion spent on fuel break segments of a given width			
						360 m wide	670 m wide	1100 m wide	2150 m wide
60 km ²	30.9%	Problem 1: min[total burn area]	94.6%	93.3%	95.1%	12.7%	87.3%	—	—
	25.9%	Problem 3: min[exp. worst burn area]	94.9%	92.6%	94.3%	6.7%	70.7%	22.5%	—
	13.7%	Problem 5: min[N node pairs w. fire spread]	95.6%	93.6%	93.6%	1%	36%	50%	14%
	5%	Problem 2: min[total burn area]	95.8%	94.6%	95.0%	—	11%	72%	17%
		Problem 4: min[exp. worst burn area]	96.2%	94.6%	95.0%	—	4.2%	65.3%	30.5%
		Problem 6: min[N node pairs w. fire spread]	96.3%	94.3%	94.0%	—	9.7%	36.1%	54.2%
100 km ²	35.6%	Problem 1: min[total burn area]	91.5%	90.0%	91.0%	25.9%	67.3%	6.8%	—
	33.5%	Problem 3: min[exp. worst burn area]	92.9%	90.0%	92.2%	17.4%	69%	13.5%	—
	16.3%	Problem 5: min[N node pairs w. fire spread]	92.6%	89.6%	88.3%	1.3%	43.2%	39.2%	16.2%
	5%	Problem 2: min[total burn area]	93.4%	91.6%	91.6%	—	10.8%	64.8%	24.4%
		Problem 4: min[exp. worst burn area]	93.8%	91.0%	92.1%	—	6.7%	58.1%	32.5%
		Problem 6: min[N node pairs w. fire spread]	93.8%	91.3%	89.3%	—	9.2%	42.0%	48.9%
150 km ²	33.1%	Problem 1: min[total burn area]	88.3%	86.6%	90.1%	21.5%	73.1%	5.4%	—
	29.8%	Problem 3: min[exp. worst burn area]	90.6%	87.6%	90.9%	15.5%	53.3%	24.4%	6.8%
	14.5%	Problem 5: min[N node pairs w. fire spread]	90.1%	86.6%	86.2%	3.3%	37.7%	27.9%	31.1%
	5%	Problem 2: min[total burn area]	90.7%	88.0%	88.0%	—	9.4%	62.1%	28.4%
		Problem 4: min[exp. worst burn area]	91.0%	87.6%	88.1%	—	9.4%	62.1%	28.4%
		Problem 6: min[N node pairs w. fire spread]	91.3%	88.0%	87.0%	0.3%	7.2%	58.6%	33.9%

* Lower objective values indicate better efficacy of fuel treatments.

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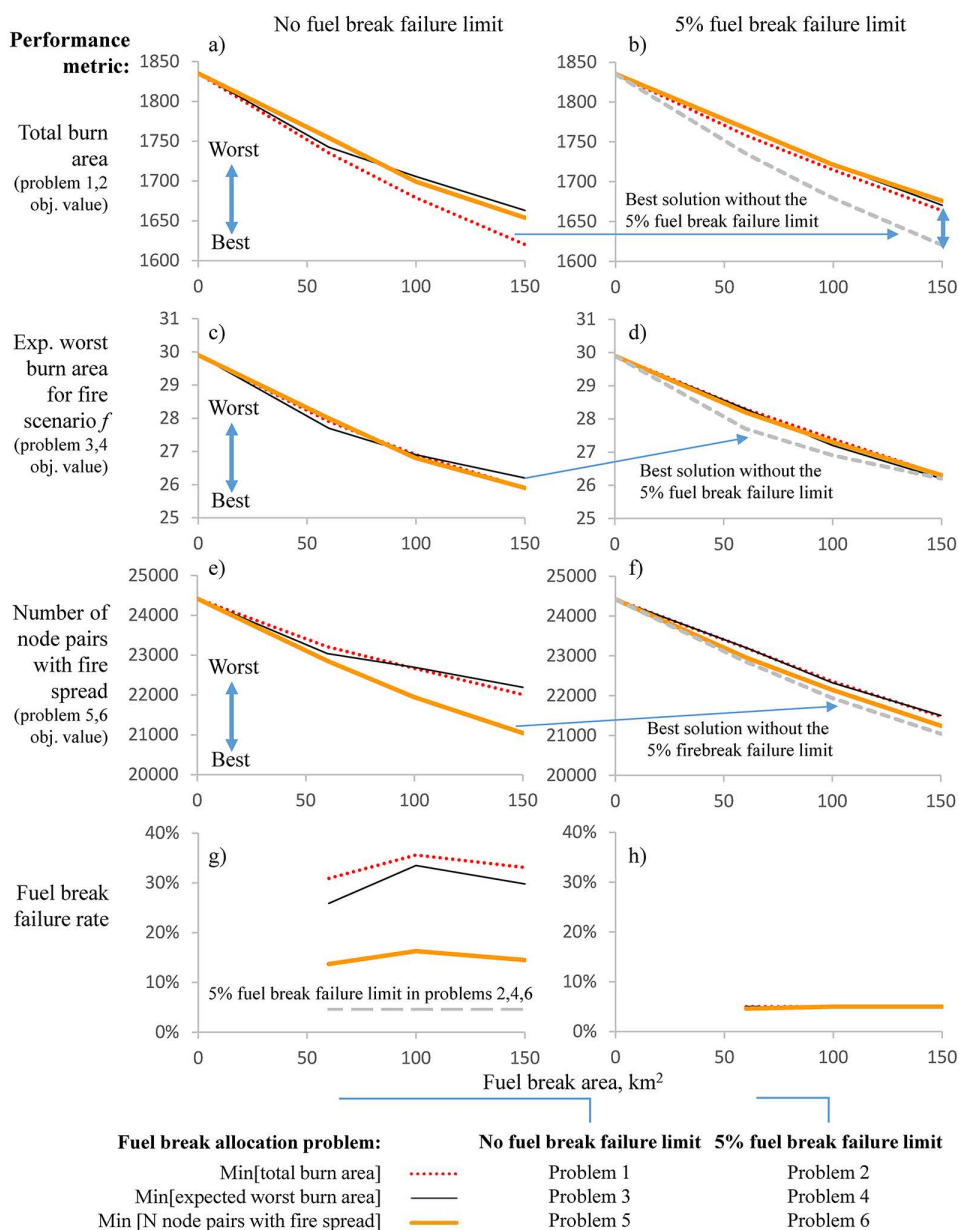


Fig 10. Fire spread risk reduction vs. the fuel break area. X-axis denotes the total fuel break area, B , in km^2 . Performance metric: a) expected burn area, no fuel break failure limit; b) expected burn area, 5% fuel break failure limit; c) expected worst burn area, no fuel break failure limit; d) expected worst burn area, 5% fuel break failure limit; e) the number of node pairs with possible fire spread, no fuel break failure limit; f) the number of node pairs with possible fire spread, 5% fuel break failure limit; g, h) average fuel break failure rate with and without the fuel break failure constraint. Lower values on the y-axis indicate better outcomes.

<https://doi.org/10.1371/journal.pcsy.0000117.g010>

Maintaining a low fuel break failure rate by keeping them wide imposed a moderate penalty on the capacity to reduce the overall fire spread potential (Fig 10F). The net reduction of the expected burn area in problems 2, 4, and 6 solutions was 25% lower than in problem 1 solutions that achieved the best overall reduction of the expected burn area (Fig 10B callout I). The trade-off between the reduction of the expected burn area (problem 1 objective) and minimizing the fire

spread connectivity (problem 5 objective) was moderate (Fig 11 callout I). Notably, the solutions minimizing the expected worst burn area (problems 3 and 4) performed poorly in both dimensions. Comparatively poorer performance was also exhibited by the solutions with a 5% fuel break failure limit, but the performance penalty was relatively small in absolute terms (Fig 11). Thus, adding a fuel break failure limit could be beneficial for reducing the risk of spread of large fires with little penalty on the reduction of the expected burn area.

3.4. Minimizing the wildfire spread potential and the protection of caribou migration routes

Protecting the caribou migration routes had a moderate impact on the reduction of fire spread risk connectivity (Fig 12, Table 5) because the model tended to allocate the fuel breaks in low-elevation areas in the eastern and northern parts of the landscape and avoided the high-elevation areas in the southwestern regions with the greatest concentration of caribou migration routes (Figs 8, 9, 13 and 14). Notable disruption of caribou migration routes was only observed in large-budget solutions to problems 3–6 (Fig 12, Table 5). The overall impact of adding the caribou migration route protection requirements on solutions minimizing the expected burn area (problems 1 and 2) was modest (Table 5). This is because the hotspots with high expected burn area tended to occur in lower-elevation areas whereas caribou migration routes did not penetrate too deeply into low-elevation regions (Fig 7C and 7D). Notably, the solutions to problems 3–6 that allocated a more dispersed fuel break pattern showed higher sensitivity to the caribou migration route protection requirements.

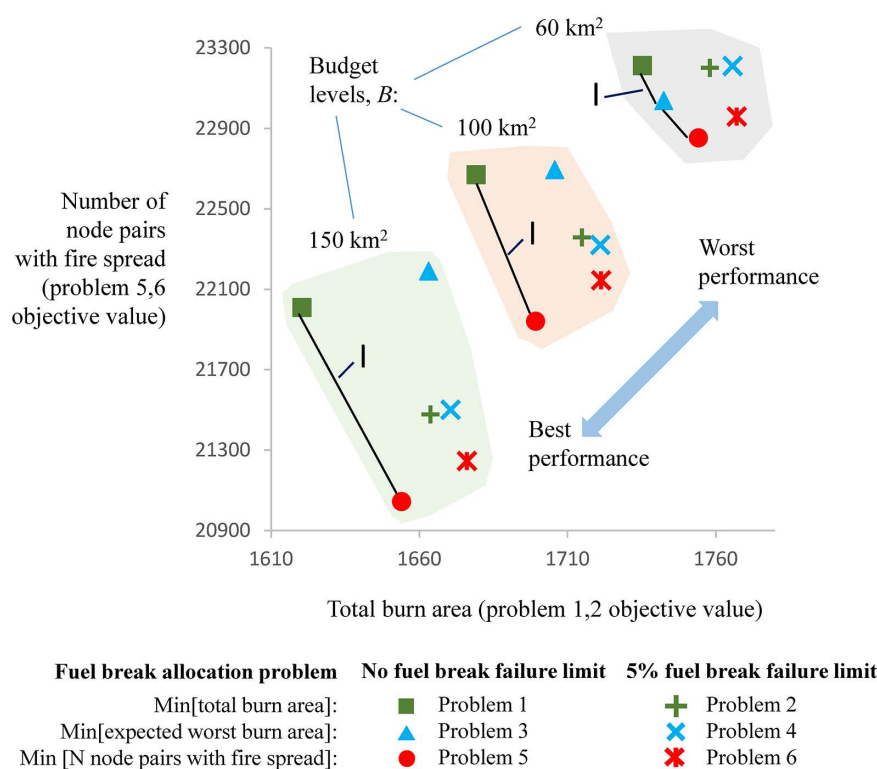


Fig 11. The trade-off between the capacity to reduce the expected burn area vs. the fire spread potential. Callout I shows the trade-off between the problem 5 solution that minimizes the fire spread potential and the problem 1 solution that minimizes the expected burn area.

<https://doi.org/10.1371/journal.pcsy.0000117.g011>

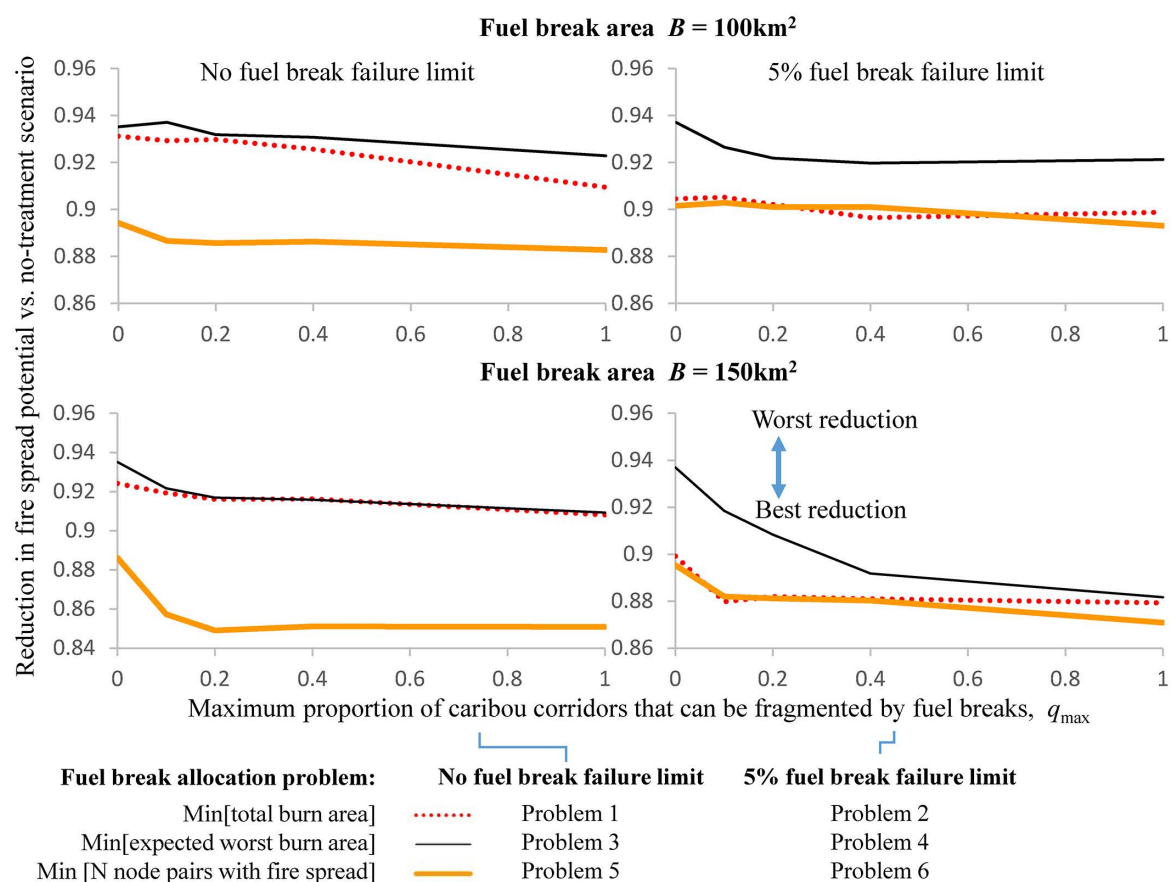


Fig 12. The trade-off between the proportion of protected caribou migration routes and the reduction of fire spread potential.

<https://doi.org/10.1371/journal.pcsy.0000117.g012>

Table 5. Impact of caribou migration route protection on the fire spread risk potential.

Fuel break area, B	Fuel break failure limit	Problem	Change in the objective value: full caribou migration route protection ($q_{\max}=0$) vs. no protection	
			Expected burn area (problem 1 objective)	N[node pairs with fire spread] (problem 5 objective)
100 km ²	No limit	Problem 1: min[total burn area]	0.8%	2.4%
		Problem 3: min[exp. worst burn area]	<0.5%	1.3%
		Problem 5: min[N node pairs w. fire spread]	<0.5%	1.3%
	5% limit	Problem 2: min[total burn area]	<0.5%	0.6%
		Problem 4: min[exp. worst burn area]	0.7%	1.7%
		Problem 6: min[N node pairs w. fire spread]	<0.5%	0.9%
150 km ²	No limit	Problem 1: min[total burn area]	1.9%	1.8%
		Problem 3: min[exp. worst burn area]	1.9%	2.8%
		Problem 5: min[N node pairs w. fire spread]	0.6%	4.1%
	5% limit	Problem 2: min[total burn area]	0.8%	2.3%
		Problem 4: min[exp. worst burn area]	2.3%	6.3%
		Problem 6: min[N node pairs w. fire spread]	0.5%	2.8%

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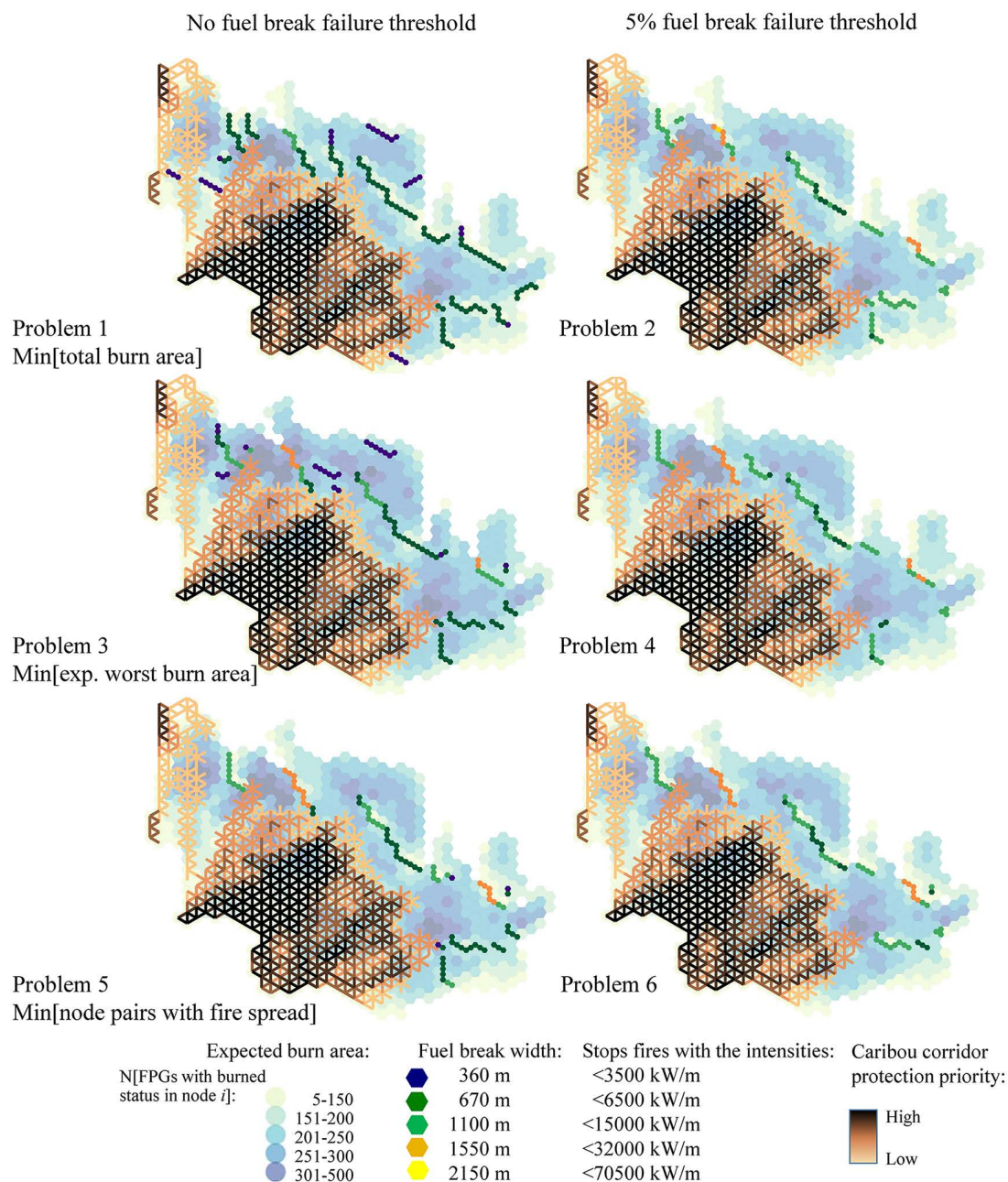


Fig 13. Fuel break allocation solutions for the total fuel break area $B = 100\text{km}^2$ with full protection of caribou migration routes. The background maps show the number of FPGs with burned status after fuel break allocation. The 5% fuel break failure threshold is applied at the whole-landscape level. The map data can be found in [S4 Appendix](#). Mapping software used: Python Matplotlib 3.4.

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4. Discussion

The proposed FPG-based approach builds on our previous work that optimized fuel treatments [47,48] in the following ways. Foremost, the new model enables selection among different fuel break types. The width of each fuel break type defines its capacity to stop the spread of a fire that burns at a particular intensity level β_{fi} , which was used to estimate the

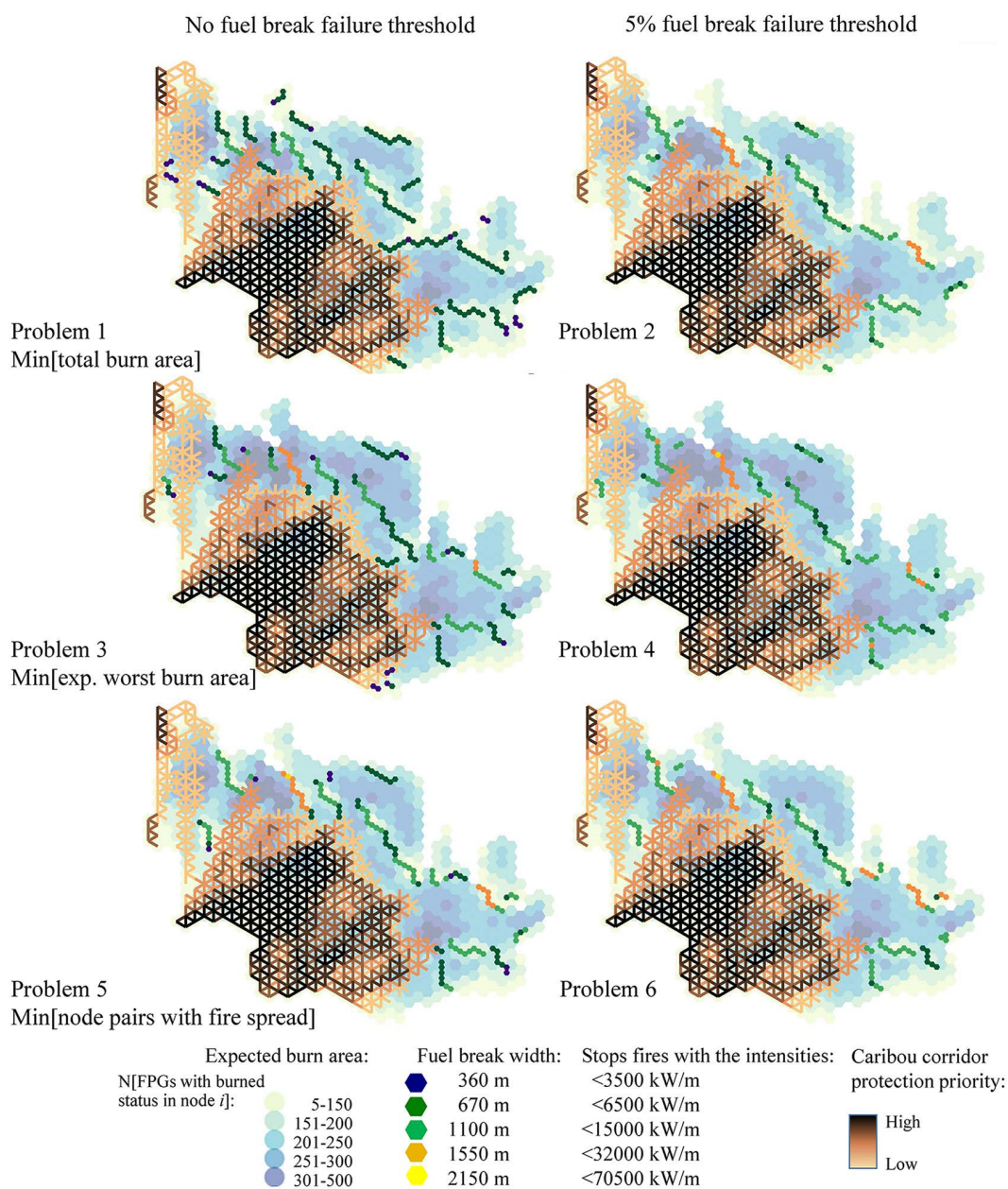


Fig 14. Fuel break allocation solutions for the total fuel break area $B = 150\text{km}^2$ with full protection of caribou migration routes. The background maps show the number of FPGs with burned status after fuel break allocation. The 5% fuel break failure threshold is applied at the whole-landscape level. The map data can be found in [S4 Appendix](#). Mapping software used: Python Matplotlib 3.4.

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maximum spotting distance from that location. Previous studies have demonstrated that the negative effects of wildfires, such as fire intensity and damage to vegetation, can be mitigated within fuel treatment boundaries [101–104]. In this context, the capacity to select a particular fuel break width makes the fuel break design better tailored to local fire spread conditions.

Another notable aspect of the proposed approach is the adoption of a scenario-based formulation where each candidate location for a fuel break is characterized by a distribution of potential fire spread outcomes. In some scenarios, the chosen fuel break width may be insufficient to contain high-intensity fires; by considering all fire scenarios it is possible to estimate the expected fuel break failure rates in those locations.

Fuel break planning is typically undertaken at the scale of individual forest sites, but the uncertain consequences of these local decisions cause impacts at a broader, landscape scale. Our approach estimates these landscape-scale impacts by tracking the fire propagation flow in a set of FPGs depicting the possible fire spread conditions in an area of interest. Note that the impact of fuel break failures could be significant if the area is predicted to experience intense fires. This makes the FPG-based approach particularly useful in regions where large fires are predicted to occur, such as boreal and montane regions of Canada, as evidenced by the record-breaking 2023 fire season [9] as well as recent wildfires in Alberta, including fires in Fort McMurray in 2016 and Jasper in 2024. Segmenting a fire-prone landscape to minimize fuel connectivity via application of problems 5 or 6 can be a workable strategy to reduce the potential risk of spread of large fires [48]. In fact, there has been some adoption of the landscape partitioning concept in part of western Canada (e.g., [105,106]), generally following the concept of Potential Wildfire Operational Delineations (PODs) adopted in the USA [107]. The FPG-based approach, thanks to its capacity to track the burn area, could help with the development of such PODs-like fire mitigation measures. In principle, our single-period model can be applied for long-term strategic planning by applying it in sequence or reformulation to a multi-period planning problem.

In boreal and montane forests of Canada, the concept of 1–2-km wide fuel breaks is becoming increasingly relevant at the landscape scale [19,20,100]. To be practical, fuel break allocation must be planned as a part of other activities which tend to create large human disturbances. In these forests, clearcut harvesting is the most common activity that creates large disturbances with reduced fuel content. This makes harvesting a feasible option for implementation of the strategic fuel break concept. The most immediate way to establish large fuel breaks is to incorporate their planning into an operational harvest planning process. Such an approach would need to evaluate the effectiveness of harvesting in terms of both reducing wildfire hazard and maximizing harvest revenue. For practical implementation, one would need to link the problem 1–6 formulations with an optimization-based harvest scheduling problem [108]. Such an integrated model would help design harvesting sequences that achieve timber supply objectives while reducing the threat of wildfires and potential timber losses.

4.1. Minimizing the expected burn damage vs. fire spread connectivity

Our results point to notable differences between mitigation strategies that reduce the expected burn area versus fuel connectivity *per se*. Minimizing fuel connectivity does not guarantee the reduction of the average burn area because fuel connectivity and the locations of hotspots with high burn risk do not always correlate. For example, patches with fuel can be well-connected to facilitate fire spread but the overall susceptibility to fire could be low. Such conditions characterize the high-elevation regions in the southwestern portion of our study area, where colder, less fire-conductive weather caused an estimated lower burn probability than in the low-elevation regions (Fig 7F).

Adding a 5% fuel break failure limit imposed a stabilizing effect on the fuel break pattern. For example, in the scenarios with total fuel break area $B = 150 \text{ km}^2$, 35.4% of the fuel break segments in solutions to problems 2,4 and 6 appeared in similar locations. In contrast, only 10% of the allocated segments were placed in similar locations in problems 1,3 and 5 solutions without a fuel break failure rate limit.

4.2. Accounting for the fire behaviour uncertainty

Our study articulates the importance of an adequate representation of the fire behaviour uncertainty space in fire mitigation planning. We depicted the multitude of fire spread outcomes in a landscape as a large set of fire scenarios with unique fire footprints. However, a finite set of fire outcomes may not fully capture the whole uncertainty space of fire

behaviours and could limit the model applicability in extreme weather conditions that are not captured by the scenario set. This emphasizes the need for accurate parameterization of the fire growth model, so the outputs can provide an adequate characterization and sampling of the uncertainty space. Notably, the issue of undervaluing the uncertainty of local fire behaviour was partially addressed by considering the worst-case local fire spread outcomes through fully connected FPGs that allowed a fire to spread to a location of concern from any adjacent upstream location. This assumption implies that the manager acknowledges the uncertainty of local fire spread and plans for the worst-case outcome. While this configuration felt sufficient to track the possibility of firebrand spotting conditions, more complex algorithms may be required to build FPGs in regions where spotting is rare or spatially constrained by local factors. Updating fire growth models to better characterize local fire spread conditions and provide a more comprehensive depiction of possible fire behaviors in the target landscape could be a valuable improvement of current fire modelling tools.

Our optimization model used a set F of FPGs generated exogenously with a spatial fire growth model. In the prediction of fire spread and severity, assumptions about ignition probabilities and weather impact the outputs of the fire growth model. This emphasizes the importance of proper calibration of the fire model and an understanding of its sensitivities to changes in the weather and ignitions inputs. Notably, the Burn-P3 model used in this study has a track record of previous applications and sensitivity analyses in Canadian forests [109–111]. Potentially, other fire growth models could be used to generate the fire scenarios. In this context, a multi-model comparison of sensitivities to weather and ignition patterns and their impacts on the fuel break configurations could be an interesting methodological exercise. Furthermore, predicted weather data, such as the daily fire weather projections presented in [89,112,113], could be adapted to simulate future fire regimes and develop fire mitigation strategies under climate change. This could be an important area of research given that climate change is expected to increase the frequency and severity of future fires in Canadian forests [114].

4.3. Impact of the caribou migration route protection requirements

The trade-off between the protection of caribou migration routes and the reduction of fire hazard was driven by the need to protect potential hotspots with large amounts of fuel with fuel breaks, while also protecting the critical caribou migration routes in those locations. Our results show a moderate impact of caribou migration route protection on the capacity of fuel breaks to reduce the wildfire spread potential. The disrupting effect of fuel breaks on caribou migration routes depended on the degree of spatial overlap between the hotspots with high burn risk (i.e., where the protective impact of fuel breaks would be most noticeable) and the locations of the caribou migration routes. In our case, this overlap was limited. However, more research into how fuel break placement may compromise the amount, connectivity and quality of caribou habitat specific to their winter range, rather than the migration routes is needed. In the Red Rock region, a decrease in caribou herd migration to their winter range is attributed to increased forest harvesting and oil and gas development [29,35,37]. Consequently, even if the migration routes are protected, their use by caribou may still decrease further if fuel breaks are located elsewhere in their winter range.

Although fuel breaks may cause a loss of caribou habitat, wildfires may do the same. Recently burned forests are likely avoided by caribou [115] and may have more forage for other ungulates that attract predators [116,117]. Because climate change is expected to lead to more frequent wildfires in the region [114], the exposure of caribou migration routes to large wildfires is expected to increase accordingly. As a compromise approach for maximizing the protection of caribou migration routes without substantially increasing the fire spread potential, one could consider less impactful fuel treatments in the migration route space, such as conversion to less flammable forest types [118]. Nevertheless, a forest patch burned by a wildfire may not be as detrimental to caribou as the same area removed by harvest [119,120], so protecting forest habitat from wildfire via forest harvest must be considered carefully. As such, comparing the habitat losses caused by wildfires with the losses caused by firebreak placement could help assess the rationale for building firebreaks in a caribou range area and could be an interesting topic of further research.

The firebreak locations prioritized by our models do not present catastrophic loss of the known caribou migration routes in the study area. However, the association of the observed decline in winter migration by the Red Rock caribou herd with increasing habitat disturbance [29,35,37] suggests that any further removal of forest through harvest will further negatively impact caribou populations viability. At a minimum, the increase of early seral habitat after the creation of fuel breaks provides movement and hunting opportunities for caribou predators [120]. Consequently, the fuel break solutions identified in our study will require additional research investigating how fuel treatments may compromise the amount, connectivity and quality of winter habitat in the study area. In a broader context, our proposed methodology could help elucidate the trade-offs of building fuel breaks in other caribou ranges, and whether additional anthropogenic disturbances might render those areas uninhabitable by caribou [29,35,37,120,121]. In turn, this could help develop wildfire mitigation options in other landscapes where large fires, human development and wildlife populations coexist.

Supporting information

S1 Appendix. Generating the Fire Propagation Graphs (FPGs) T_f
(PDF)

S2 Appendix. The firebrand spotting distance calculation.
(PDF)

S3 Appendix. Fuel break allocation solutions with a depiction of the fuel break failure rates.
(PDF)

S4 Appendix. Network-based data.
(ZIP)

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