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Wildfire Risk to Caribou Conservation Projects in Northeastern Alberta

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Canada

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Executive Summary

The boreal forests of Alberta have dense networks of seismic exploration lines which have been shown to contribute significantly to the decline in woodland caribou (*Rangifer tarandus caribou*) populations throughout the region due to the effects they have on increasing predation risk to caribou. In order to improve habitat quality for caribou and to reduce predation on caribou by wolves, oil-and-gas companies are investing significant resources in the restoration of many of these seismic lines in key areas. Wildfire is a common natural disturbance throughout northern Alberta and is very likely to increase in frequency and severity under climate change. Fires that occur in the boreal forest are capable of eliminating hundreds of thousands of hectares of woodland caribou habitat in a single event, and could potentially erase all of the forests in which these seismic restoration projects are occurring.

In order to support sound conservation decisions and to minimize the wildfire risk to habitat restoration investments it is important to know what the likelihood of a wildfire occurring at every point on the landscape, and what mitigation measures would be the most effective to minimize this hazard. There is also substantial interest in understanding how climate change may affect the wildfire probability of the landscape. To address this question we undertook a comprehensive wildfire risk assessment of the landscape that contains these major caribou restoration and recovery initiatives in north-eastern Alberta. This project was designed to use the Burn-P3 model to determine the burn probability across the COSIA management zone, and more specifically:

A) What is the wildfire risk to the restored seismic line areas within the Cold Lake Caribou Range?

B) Where are the best places on the landscape to invest in caribou conservation efforts with respect to reducing wildfire risk?

C) Do intensive management zones designed to reduce vegetation flammability and potential ignitions reduce the wildfire risk, and if so, to what extent?

D) How will climate change affect the burn probability of the landscape (Appendix A)?

We conducted a coarse-scale baseline burn probability assessment for the oil-sands lease areas of the landscape (COSIA area) and a finer-scale assessment of the Cold Lake Caribou Range area. We found that recent large burns and waterbodies provided “shields” that reduced burn probability on their leeward sides (to the east). Using this information, we held a workshop with our project partners to develop mitigation scenarios, where we opted to concentrate conceptual mitigation activities in specific parts of the landscape in order to mimic the shielding effect of waterbodies and large recent burns. We used parts of the landscape under active industrial management as “intensive management zones” within which we could focus mitigation efforts and determine the effects of large-scale conversion of coniferous forests to deciduous and reductions of potential ignitions on the burn probability of leeward restored caribou habitat zones. We found that these intensive management zones were effective at reducing burn probability and wildfire hazard. Assuming that the fuel changes caused by silvicultural species conversion would last for many decades, this reduction in hazard would be effective for a considerable period of time. We did find, however, that the effectiveness of these treatments declined rapidly as distance from the treatment zones increased. In general, the effectiveness of any mitigation measures is localized. Climate change scenarios showed that by 2050 and 2080, the COSIA area will see marked increases in burn probability (Appendix A).

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Quinn Barber is a spatial ecologist and wildfire scientist with the Canadian Forest Service. He has two MSc's in Forest Biology from the University of Alberta and Albert Ludwigs University of Freiburg, where he wrote his thesis on climate change velocity and climate change impacts on rare vascular plants. Quinn's research areas include wildfire, caribou ecology, LiDAR, and the ecological impacts of climate change.

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Alberta

Introduction

In the western Canadian boreal forest, wildfire is the dominant high-mortality disturbance agent affecting vegetation. On average over the past 50 years, between 0.22% (Bergeron et al. 2004) and 0.41% (Tymstra et al. 2005; Cumming 2000) of the boreal forest in Alberta burns annually. The range in sizes of fires is broad with 97% of the area burned occurring in a few very large fires (Stocks et al. 2002; de Groot et al. 2013). These large fires can burn hundreds of thousands of hectares (Figure 1) in a matter of days and can threaten human values when they burn into populated regions, as evidenced in Slave Lake (2011) and Fort McMurray (2016). Most fires, however, burn in isolated areas and go unnoticed by the general public. While the landscape is well adapted to wildfire as an ecological disturbance, there is increasing evidence that the trends in wildfire sizes and severity are increasing (Bergeron et al. 2004; Kasischke and Turetsky 2006; Giglio et al. 2010; Wang et al. 2017), potentially causing significant damage to ecological resources that are themselves being squeezed out in a landscape that is steadily becoming more developed (Burton et al. 2014; ABMI 2017) .

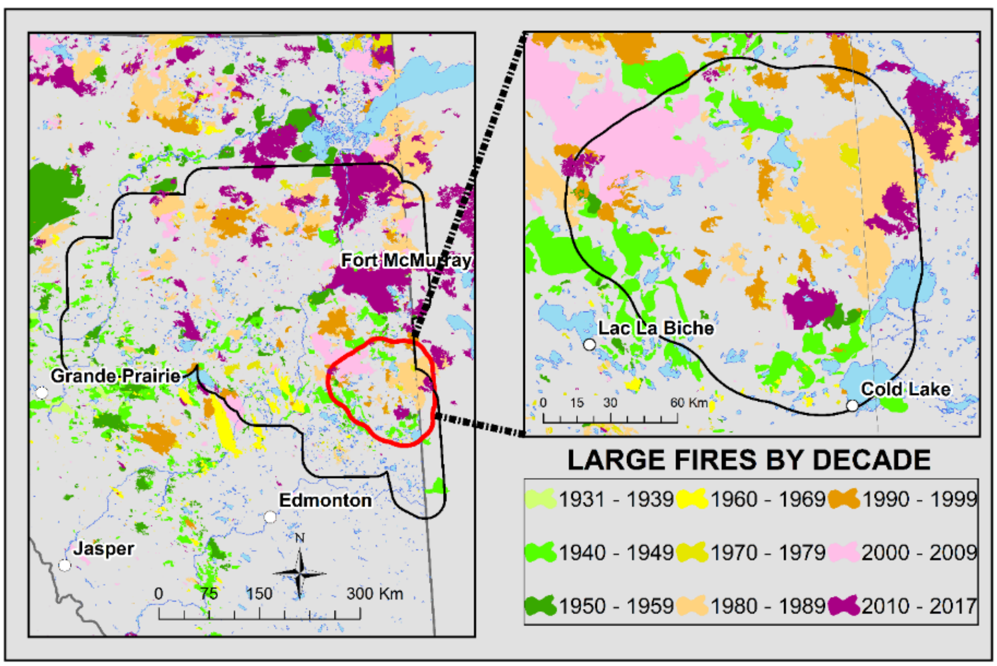

Figure 1: Class A (≥200 ha) fires occurring throughout the study area. Note that many older burns are “hidden” or erased by more recent fires.

Being able to predict when and where fires may occur on the landscape, and how intense fires can become is important for natural, non-renewable, and human resource management. Wildfire hazard is highly variable (but predictable) across and space and time (Miller and Ager 2013; Scott et al. 2013). Wildfire risk is defined as the combination of the hazard and impact a fire would have on a given value (Finney 2005). In order to assess risk, one must first examine wildfire hazard, which sets aside the impact of fires on particular values, and focuses solely on the likelihood and intensity of a fire that may occur at a given point (Calkin et al. 2010). There are numerous methods to examine wildfire hazard, and one of these is to model burn probability using Burn-P3 (Parisien et al. 2005). Burn-P3 has been used extensively to examine wildfire hazard (Parisien et al. 2007, 2011, 2013; Miller et al. 2008; Wang et al. 2014, 2016; Whitman et al. 2017), and uses a Monte-Carlo approach to model a large number (thousands) of iterations, with each iteration representing a single year of wildfires. Burn-P3 simulates the spread fires using the Prometheus fire growth model (Tymstra et al. 2010) on a gridded landscape with known fuels and topography. Burn-P3 uses probabilistic draws of ignition locations and fire weather conditions, both derived from historical data.

Moving from hazard to risk requires understanding the impact fires will have on highly valued resources and assets (HVRAs), and these impacts may be either positive or negative (Calkin et al. 2010; Thompson et al. 2011). Positive impacts include the creation of diverse forest age-class structures, germination of new seedlings, regeneration of fire-dependent plants, and the creation of habitat for early seral stage species, among others (Johnson 1996). Negative impacts include, but are not limited to, the loss of human life, destruction of houses, damaged oil-and-gas infrastructure, and the loss of key breeding habitat for various wildlife species (Thompson et al. 2011). The northern Alberta boreal landscape is not unlike many other forested landscapes where many different values with different risk profiles overlap. The boreal forest is home to numerous wildlife, plant, and other species, many of which directly or indirectly depend upon the physical effects of fires. However, while many elements in the boreal forest require fire, others need to be protected from it such as human life, communities, and the oil-and-gas industry. Managing fire is complex, we need to protect key resources, yet recognize the need to allow fire to burn in many parts of the landscape for key ecological processes.

Mitigation of wildfire hazard can either be done by altering fuels (vegetation), or reducing the number of fires that occur on the landscape. In the short term, changing fuels can only be achieved through silvicultural methods such as thinning, pruning, or harvesting, and by the use of prescribed fire. Timber harvesting either focuses on changing the physical structure of the fuels by thinning (to reduce crown bulk density) or pruning (reduce crown base height), or full harvesting and replanting with a different species (thereby changing the fuel type entirely). A key question when deciding what mitigation method to use, and where to do it, is whether management activities are best spread lightly across the landscape to affect a wider area, or focused on intensive management zones while leaving others relatively intact (Kingsland 2002). We know that once fires burn, the same area has a reduced likelihood of burning for a significant period of time (Krawchuk and Cumming 2009; Héon et al. 2014), and this burned landscape serves as a temporary "shield" for adjacent resources (Erni et al. 2018). If old burns act as barriers to fire spread for a period of several years, can we use intensive management to alter the fuels in one part of the landscape to reduce wildfire risk in other locations?

A critical ecological resource on this landscape is the woodland caribou (*Rangifer tarandus caribou*). Woodland caribou is a federally listed "threatened" species in Canada (Government of Canada 2017), a status which confers legal requirements to protect them and their habitat. Caribou populations are particularly threatened in Alberta, where most populations are in rapid decline (Hervieux et al. 2014). High predation risk is the main cause of this decline, driven by increasing forest fragmentation which is the result of the extensive network of linear disturbances resulting from oil-and-gas exploration (Latham et al. 2011). Wolves use these extensive linear disturbances as travel corridors and as pathways into fens and bogs, which have traditionally provided caribou refuge, since deer and moose are preferred prey for wolves (James et al. 2004, Latham et al. 2011). Furthermore, wildfire also has impacts on caribou by destroying valuable cover that protects them from predation, destroys the lichens which caribou depend upon in winters with heavy snowpacks, and by creating young seral stage forests which boost deer and moose populations, which in turn boost wolf numbers. Oil-and-gas companies in the Alberta boreal forest have been restoring linear disturbances to contribute to woodland caribou conservation, and are actively changing business practices to reduce the likelihood of wildfire impacting critical caribou habitat. However, these activities are expensive, and it would be ideal if the landscape could be "triaged" to identify which parts are least likely to burn, in order to maximize the value and extend the duration over which these restoration efforts would be effective.

Goals and Objectives

The objectives of this study were to investigate the following questions:

A) What is the wildfire risk to the restored seismic line areas within the Cold Lake Caribou Range?

B) Where are the best places on the landscape to invest in caribou conservation efforts with respect to reducing wildfire risk?

C) Do intensive management zones designed to reduce vegetation flammability and potential ignitions reduce wildfire risk, and if so, to what extent?

Study Area

We conducted our study at two separate spatial scales: a coarse-scale analyses across a large landscape, and a fine-scale analyses conducted in a smaller region within the same large landscape. Our large study area (hereafter the "COSIA area") covered 19.7M ha, which includes the three contiguous Oil Sands Management Zones of northern Alberta plus a 25 km buffer surrounding them (see Figure 2). The finer-scale study area consists of 2.1M ha centered on the Cold Lake Caribou Range (hereafter the "Cold Lake" area) with a 25 km buffer (see Figure 3).

The majority of the study area is forested, although a small area featuring agricultural land use (i.e. the 'White Zone') is located on the southern and western limits of the study area. Included in the study area are several large municipalities, including: Bonnyville, Cold Lake, Fairview, Fort McMurray, High Prairie, Lac La Biche, Lloydminster, Manning, and Slave Lake. Oil-and-gas activity is prevalent throughout the study area and is centered around the municipalities of Fort McMurray, Cold Lake, and Peace River. Forested zones of the study area are managed by forestry companies for both coniferous and deciduous trees. See Figures 2 and 3 for an outline of some of the key features on this landscape.

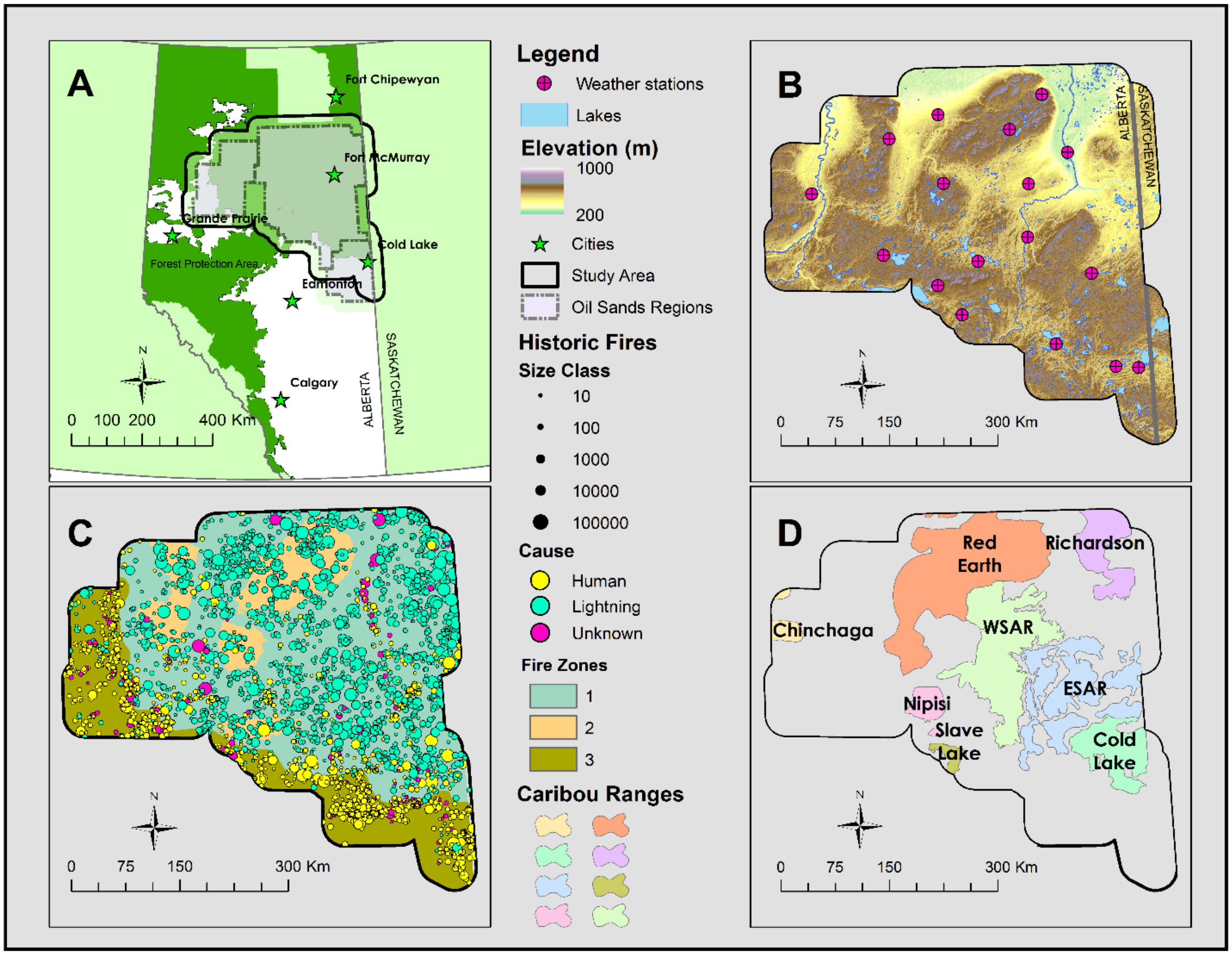

Figure 2: Key features of the COSIA landscape zone (plus 25 km buffer). A) Location of the Oil Sands Regions, together with the 25 km buffer that defines the COSIA Area. This map also shows the location of the Forest Protection Area of the province of Alberta. B) Elevation of the area, in addition to the locations of major bodies of water and weather stations used to develop weather inputs for the model. C) Fire history of the landscape, dot size represents size class of fires, colour indicates the cause. This panel also shows the three fire zones used in the modeling. D) Approximate Caribou ranges in the COSIA landscape. The fine scale study was restricted to the Cold Lake Caribou Range.

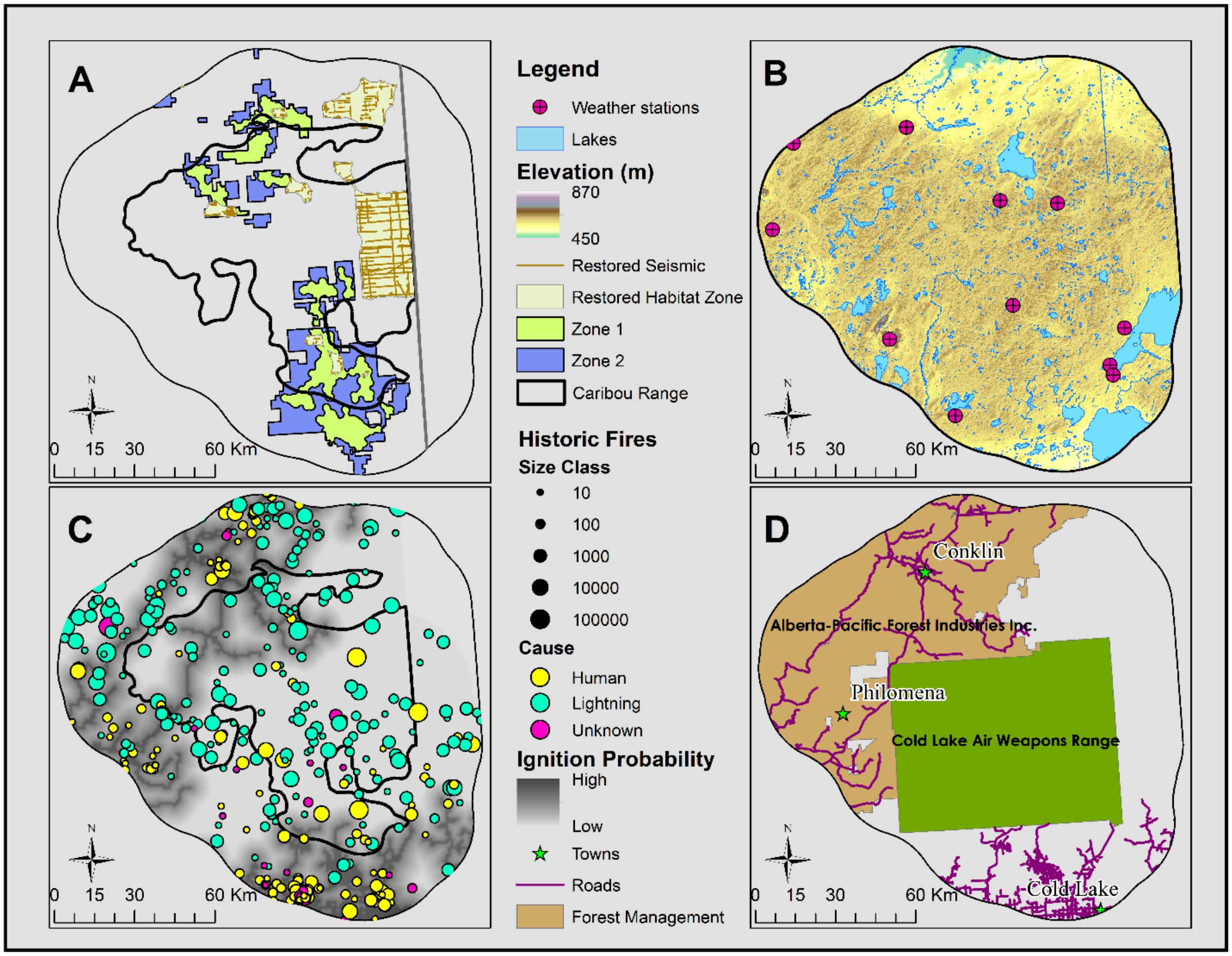

Figure 3: Key features of the Cold Lake Caribou Range (plus 25km buffer). A) Two zones used to define management scenarios. Zone 1 is the buffered location of the majority of oil-and-gas facilities in the area, and Zone 2 is the location of the Active Oil Sands Leases. Also shown on this panel is the location of the restored seismic lines, which are then buffered to show the restored habitat zones. B) Elevation of the area, major bodies of water and weather stations used to develop weather inputs for the model. C) Fire history of the landscape,dot size represents the size class of fires, colour indicates cause. This panel also shows the human caused fire ignition density grid used in the modeling. D) Other important features of the landscape, incudling timber harvesting areas, the Cold Lake Air Weapons Range, and roads throughout the region.

The Alberta boreal forest is a mosaic of wetlands (marshes, fens, and bogs) drier forested uplands, and open water. Boreal wetlands feature cold, poor soils dominated by black spruce (*Picea mariana*) and eastern larch (*Larix laricina*). Upland forests are composed primarily of white spruce *(P. glauca),* aspen *(Populus tremuloides*), and jack pine (*Pinus banksiana*) in mixed proportions. The Alberta Natural Subregions are 21 regions of Alberta, generally characterized by similar vegetation, climate, elevation, latitude, and other physiographic differences. The COSIA area encompasses a large part of northern Alberta, and covers nine Natural Subregions: the Lower Foothills, the Central Parkland, the Peace River Parkland, the Dry Mixedwood, the Central Mixedwood, the Lower Boreal Highlands, the Upper Boreal Highlands, the Athabasca Plain, and the Kazan Uplands (Table 1, Table 2, Figure 4). The Cold Lake Area covers three Natural Subregions: the Lower Boreal Uplands, the Dry Mixedwood, and the Central Mixedwood.

Table 1: Characteristics of Alberta Natural Subregions (NSR) (Natural Regions Committee 2006) within the COSIA study area.

Alberta Natural Subregion	Key characteristics
Lower Foothills	Cold winters and higher winter snowfalls. Mesic, closed-canopy mixedwood stands of lodgepole pine, white spruce, balsam poplar, and aspen.
Central Parkland	Primarily agricultural land. Remnant aspen and parkland vegetation in uncultivated areas. Intermediate climate that is generally warmer and drier than the boreal forest to the north.
Peace River Parkland	Primarily agricultural land. Upland forests of aspen and white spruce. Somewhat drier and warmer than adjacent NSRs.
Dry Mixedwood	Warmer summers and milder winters than other Boreal regions. Aspen mixedwood forest with some white spruce and jack pine, scattered peatlands. Some agriculture in suitable areas.
Central Mixedwood	Aspen, white spruce, and jack pine on uplands, interspersed with extensive peatlands. Wetter and with cooler winters than other NSRs to the south, but greatly variable with latitude.
Lower Boreal Highlands	Moister and cooler than adjacent NSRs. Diverse mixedwood forests of aspen, balsam poplar, black and white spruce, lodgepole pine, jack pine, and white birch. Peatlands in depressions.
Upper Boreal Highlands	Moister and cooler than Lower Boreal Highlands. Mostly coniferous forests with extensive peatlands in topographic depressions.
Athabasca Plain	Coarse-textured gravels and sands promote widespread jack pine forests and shrublands. Cold winter, but relatively warm summers compared to other boreal Natural Subregions.
Kazan Uplands	Sparsely-vegetated bedrock with lichens on exposed bedrock and elsewhere jack pine, black spruce and aspen. Warm summers and extremely cold winters.

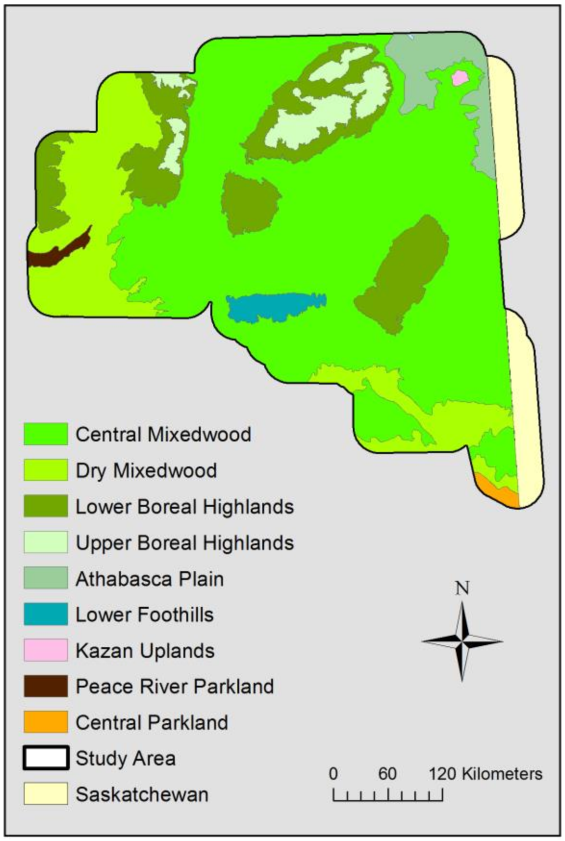

Figure 4: Alberta Natural Subregions (Natural Regions Committee 2006) of the COSIA area.

Table 2: Natural subregion (Natural Regions Committee 2006) climatological descriptions including mean annual temperature, mean annual precipitation, and frost-free period.

Natural Subregion	Mean Annual Temperature (°C)		Mean Annual Precipitation (mm)		Frost-Free Period (days)		Percent of COSIA area
	Mean	Range	Mean	Range	Mean	Range	
Lower Foothills	1.8	27.5	588	269	94	78	9.9%
Central Parkland	2.3	31.2	441	169	102	47	12.7%
Peace River Parkland	1.5	31.8	450	160	102	28	0.3%
Dry Mixedwood	1.1	32.7	460	224	98	58	19.9%
Central Mixedwood	0.2	34.9	477	301	97	43	39.7%
Lower Boreal Highlands	-1	35.0	495	226	97	37	11.0%
Upper Boreal Highlands	-1.5	34.9	534	142	97	23	1.8%
Athabasca Plain	-1.2	39.7	428	185	103	16	3.2%
Kazan Uplands	-2.6	41.7	380	136	99	11	0.1%

The wildfire regime is characterized by large, stand-replacing fires, sometimes exceeding 100,000 ha in size (Parisien et al. 2006) and burning at high intensities beyond suppression capability (Armstrong 1999; Bergeron et al. 2004; Tymstra et al. 2005). The fire season generally runs from early April through late September, however, fires are possible in both March and October (Tymstra et al. 2005). Fires are primarily human-caused in the spring and lightning-caused in the summer (Tymstra et al. 2005). The historical fire return interval in much of the Boreal Mixedwood region is highly variable, with little agreement on the numbers. Estimates of the fire return interval range in some studies from 30-130 years (Larsen 1998) to 200+ years (Stocks et al. 2002; Tymstra et al. 2005).

Urban development and agriculture represent a very small portion of the land base, and human population density is low. However, industrial land-use is extensive, consisting of a network of oil-and-gas wells, mines, forestry cut blocks, industrial facilities, and linear features including pipelines, seismic exploration cut lines, roads, and other similar disturbances. Seismic exploration lines (hereafter "seismic lines"), vary in width between two and ten metres and are now the largest contributor to forest fragmentation in northern Alberta. Seismic line densities in northern Alberta average approximately 1.5 km/km^2, often exceeding 10 km/km^2 in the most disturbed areas (van Rensen et al. 2015). These linear features often fail to recover to a pre-disturbance state, with approximately one-third of these features failing to recover even 50 years after the initial disturbance (van Rensen et al. 2015; Lee & Boutin 2006). We chose to use a series of restored linear features in the Cold Lake area to be used as an example of a highly-valued resource and asset (HVRA) features against which we could conduct our fire risk analyses.

There are eight caribou herds within the study area, including: Red Earth, West Side Athabasca River (WSAR), Richardson, East Side Athabasca River (ESAR), Cold Lake, Nipisi, Slave Lake, and Chinchaga. All nine of these herds have been classified as "not self-sustaining", defined as a shrinking population in danger of extirpation (Environment Canada 2011, 2012). The Cold Lake caribou herd has experienced one of the most severe population declines of any Albertan herd, with a cumulative population change of -86.9% from 1994 to 2012 (Hervieux et al. 2013).

Methods

We modeled wildfire hazard (as of 2016) over the COSIA and Cold Lake areas using the Burn-P3 model (Parisien et al. 2005) to develop a baseline. Using outputs such as burn probability, fire intensity, and fire hazard generated from the current state assessment we held a workshop with our project partners and stakeholders to develop a range of mitigation scenarios that could reduce the wildfire hazard and risk posed to the restored seismic lines within the Cold Lake caribou range. We then modified baseline model inputs to reflect how the mitigation scenarios would affect ignition probabilities and fuel composition and then ran the Burn-P3 model again with these modified inputs. The mitigation scenario outputs were then compared to the baseline to determine changes to burn probability, fire intensity, fire hazard, and firesheds.

Burn-P3 Modelling

We used the Burn-P3 fire simulation model (Parisien et al. 2005) to model burn probability, fire intensity, crown fraction burned, and fire size across the COSIA area to evaluate wildfire hazard. These same measures were modelled in the Cold Lake Caribou Range, in addition to evaluating the effectiveness of fuel and ignition treatments. Burn-P3 is a Monte Carlo simulation model based on the Prometheus fire growth engine, and simulates ignition and spread of fires across the landscape. Burn-P3 geographically places fires based on a probability surface, and grows them using a probability distribution of weather conditions based on recent historical weather. To conduct this analysis, we needed a current and accurate representation of vegetation, a detailed digital elevation model, weather data, and to understand the locations and probabilities of fire ignitions. Vegetation in the Burn-P3 model is represented by Fire Behaviour Prediction System (FBP) (Forestry Canada Fire Danger Group 1992) fuel types. Burn-P3 accounts for changes in plant phenology by using different fire behaviour algorithms depending on whether broadleaf deciduous vegetation has leaves or not, and by "curing" grasses at the appropriate time of year in the model. Furthermore, seasonal changes in fire behaviour are modelled by stratifying the fire environment inputs by season. Detailed digital elevation data supplies topographic information necessary to spread fire in a realistic manner.

Each Burn-P3 model run (hereafter "iteration") simulated a single year of wildfire, and we evaluated each model scenario by running 20,000 Burn-P3 iterations (approximately 120,000 fires). The primary model output consisted of the burn probability (hereafter "BP"), defined as the proportion of times a pixel will experience fire relative to the total number of iterations. Secondary model outputs included: mean fire intensity, measured in kW/m^2; mean crown fraction burned, the percentage of the forest crown consumed by fire; and simulated fire perimeters. The following section details the Burn-P3 data inputs and model-building process.

Data inputs

Preparation of inputs for running the Burn-P3 model involves compiling and creating numerous data inputs related to the vegetation, weather, and fire history of the COSIA and Cold Lake areas. These inputs are listed in Table 3.

Table 3: Static and stochastic inputs used to model burn probability. See Figures 1, 2, 3, and 5.

Model Input	Data Type	Description
Static inputs:		
Fuels	Categorical raster	Canadian Forest Fire Behavior Prediction System fuel type classifications and non-fuel features derived from the provincial 2014 fuel grid and the national fuel grid 2015. See methods for how these two data sources were combined (Figure 5). Resolution of 100m for Cold Lake Caribou Range, 250m for the COSIA landscape.
Topography	Continuous raster	Elevation data supplied by province of Alberta from LIDAR sampling at 1m resolution, re-sampled to 100m resolution. See Figure 2 and 3.
Fire zone	Categorical raster	For COSIA area fire zones formed according to mean-annual ignition densities (See Figure 2). For the smaller area we did not divide it into fire zones.
Seasons	Setting	Start and stop dates for fire weather, grass curing, and deciduous green-up change: - Spring = Mar-1 to May-31 (85 % grass curing, leafless broadleaf deciduous) - Summer = May-31 to Oct-31 (60 % grass curing, broadleaf deciduous green-up)
Stochastic inputs:		
Number of fires	Frequency distribution	Number of fires ≥ 50 ha per year (or iteration). Historical records of the number of fires ≥ 50 ha per year were fitted to a negative binomial distribution. (Figure 6).
Escaped fire rates	Frequency distribution	Proportion (%) of fires ≥ 50 ha occurring in each combination of season, cause (human, lightning), and fire zone. (Figure 7)
Spread days	Frequency distribution	Number of days a fire is expected to spread. Distribution was derived from from Moderate-Resolution Imaging Spectroradiometer (MODIS) hotspot detections for fires ≥ 200 ha using the weighted by mean and distance method described in Parks (2014). (Figure 8)
Spread hours	Frequency distribution	The number of hours per day a fire is expected to spread. This input was not derived from empirical data. Burning hours were calibrated so that the distribution of simulated fire sizes was similar to historic fire records for years 1961 to 2014.
Ignition locations	Continuous raster	Relative probability surface of human ignition locations is based on 1961-2014 fire history records and the model assigned ignitions based on these probabilities. Lightning ignitions were located randomly with equal probability in all areas stratified by each fire zone by the model. See Figure 3.
Daily fire weather	Numeric list	Daily weather conditions observed at noon MST and associated Canadian Fire Weather Index System codes and indices partitioned by season and fire zone. Weather observations from 13 stations with ≥ 20 years of historical records were used. The Cold Lake area was modeled using a 7-station subset of these weather observations. The Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI) and Fire Weather Index (FWI) were recalculated for stations with scaled wind speeds. We then extracted days with fire-conducive conditions using a FWI threshold of 18 or greater See Figures 2 and 3 for locations of weather stations used.

Fuels

Fire modelling requires that vegetation cover for the study area be classified and converted to fuel types, as described by the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Hirsch 1996). Fuel type is "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behaviour under defined burning conditions" (Merrill and Alexander 1987). Fuel characteristics are an important determinant of fire behaviour, including rate of spread, fuel consumption, fire intensity, and fire growth for 16 benchmark fuel types. Fuel types are grouped into five major fuel types groups: coniferous, deciduous, mixedwood, slash, and open grass. Non-burnable areas consisted of water, vegetated nonfuel, and urban areas, although under certain conditions the latter two fuel types may also burn.

The current fuel composition of the landscape was represented by a hybrid of the annually updated fuel grid supplied by the Government of Alberta Forest Protection Branch and a national scale fuel grid (Government of Canada (GOC) fuel grid) developed from remotely sensed vegetation data collected and evaluated by Beaudoin et al. (2012). The GOA fuel grid is derived from several sources of vegetation data, including the Alberta Vegetation Inventory (AVI) (Resource Information Branch 2005) and the Alberta Ground Cover Classification (Sanchez-Azofeifa et al. 2005) system and is updated on an annual basis to account for disturbances such as forest harvesting, wildfires, and other land use dispositions. The AVI is manually interpreted from air photos, and has a minimum polygon resolution of 2 ha. The GOA converts the AVI to FBP System fuel types using a translation matrix and transforms it into a 1-ha resolution raster grid. The FBP fuel types present in the COSIA study area are C-1 (spruce lichen woodland), C-2 (boreal spruce), C-3 (mature lodgepole pine), C-4 (immature lodgepole pine), C-5 (red and white pine), D-1/D-2 (leafless/leafy aspen), M-1/M-2 (leafless/leafy mixedwood), S-1 (jack pine slash), S-2 (spruce slash), and O-1 (grass).

The GOA fuel grid is at a spatial resolution of 100m. One source of inaccuracy in the GOA fuel grid is that any area that has experienced a fire within the past 20 years is classified as "vegetated non-fuel". While past fires do limit subsequent fires from occurring for a period of time, they may reburn again on average after only 5 or 6 years, or even earlier (Krawchuk and Cumming 2011; Parks et al. 2017). Unlike the GOA fuel grid that is updated every year, the GOC fuel grid was last updated in 2011 and is derived from MODIS satellite data at a resolution of 250m pixels. The GOC fuel grid is 6 years old at this time, and we feel confident that by overwriting any of these old fires that are more than 6 years old and less than 20 years old with the GOC fuel grid will give us the most accurate picture of vegetation currently on the landscape in 2017. The fuel maps for the COSIA and Cold Lake study areas are shown in Figure 5**.** We maintained the 100m resolution for the Cold Lake Area, but resampled the fuel grid to a 250m resolution for the large landscape as we could not model such a large area at a 100m resolution.

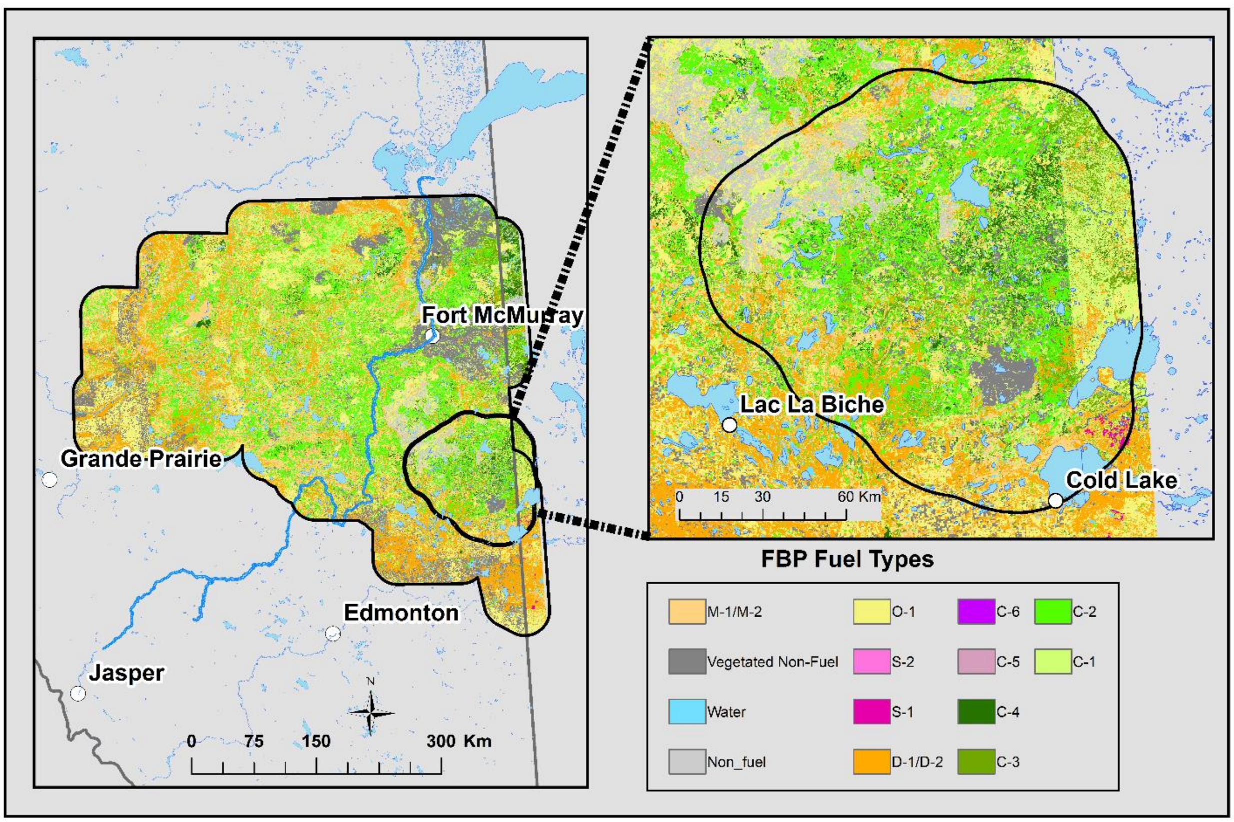

Figure 5: The Canadian Fire Behaviour Prediction (FBP) system fuel types in the COSIA landscape, and the Cold Lake landscape. The discontinuity (edge effect) at the Saskatchewan border is due to no Alberta Vegetation Inventory data present for that province, and the National Fuel grid has a different resolution.

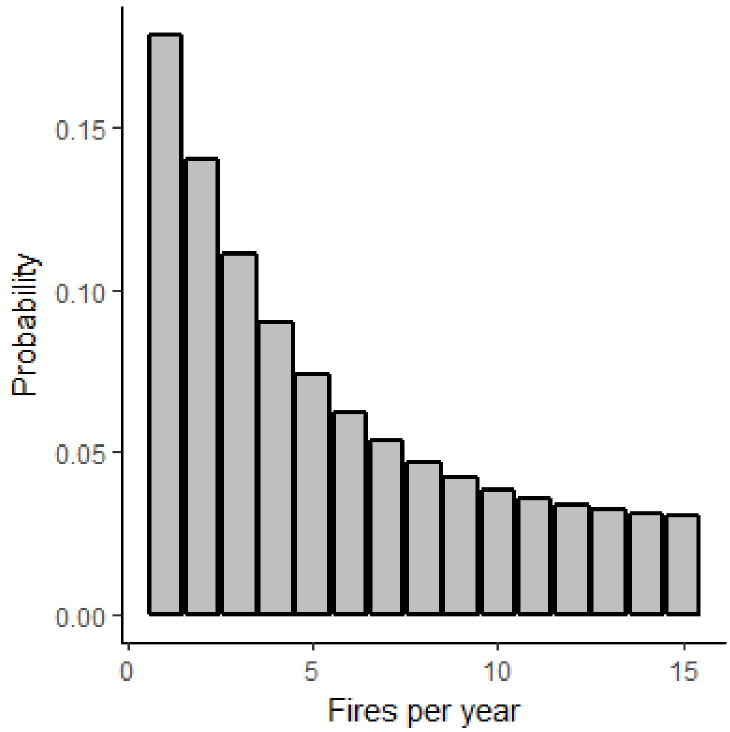

Figure 6: distribution of the number of fires Burn-P3 modelled per iteration for the Cold Lake Area.

Topography

Topography was represented by a Digital Elevation Model (DEM) provided by the Government of Alberta. This DEM was derived from 1m-resolution LIDAR data, and resampled to 100m for our modeling efforts. The DEM for the study area is shown in Figures 2 and 3.

National Fire Database

Burn-P3 relies on historical fire data as a basis for accurately modelling real-world fires. The Canadian National Fire Database (CNFDB) is a federal database of forest fire records including data from provinces, territories, and Parks Canada (Natural Resources Canada 2018). The CNFDB database includes forest fire data dating from 1946 to 2016 (and updated annually), and varies in source and quality between sourcing agency and report date. These fires are shown in Figures 1, 2 and 3. We used records from the CNFDB to determine the number of fires per year, the likely location of those ignitions, the seasonality of those fires, and whether those fires were human-caused or lightning-caused. These parameters were based on all fires that occurred within the COSIA area since 1960 and exceeding 50 ha in size (Figure 9). These records were also used for model calibration by comparing the historical fire size distribution against the modelled fire size distribution.

Fire Zones

We mapped all known fires in the region to determine if there were distinct patterns in cause, seasonality, and/or size of fires in different parts of the study area. Fires within the COSIA area were naturally grouped by their cause, the season during which they occurred, and the average fire weather conditions at the time of the fire. Based on a qualitative analysis of these factors, we subdivided the COSIA area into three fire zones: the Boreal Mixedwood (zone 1), the Boreal Uplands (zone 2), and the Human-dominated zones (zone 3) (Figure 7). The Boreal Mixedwood was representative of average conditions across the COSIA area, characterized by large fires that were predominantly lightning-caused and randomly-distributed. The Boreal Uplands was defined by higher elevations and extensive mixedwood forests, albeit a colder climate than the Boreal Mixedwood. The Human-dominated zone varied significantly from the first two zones, and was characterized by a high number of human-caused spring fires burning in grasslands, agricultural zones, and near transportation corridors. The majority of the Cold Lake area was encompassed by the Boreal Mixedwood fire zone, and for simplicity, it was considered to be a single fire zone.

Seasons

In the study area, modeled fires occurred between 1 April and 31 October, which spans the period when almost all of the large wildfires occur. In addition, we stratified this period into season. Seasons were established to determine the start and end dates of the different periods of fire activity caused by spring grass green-up, spring aspen leaf flush, and summer/fall grass curing.

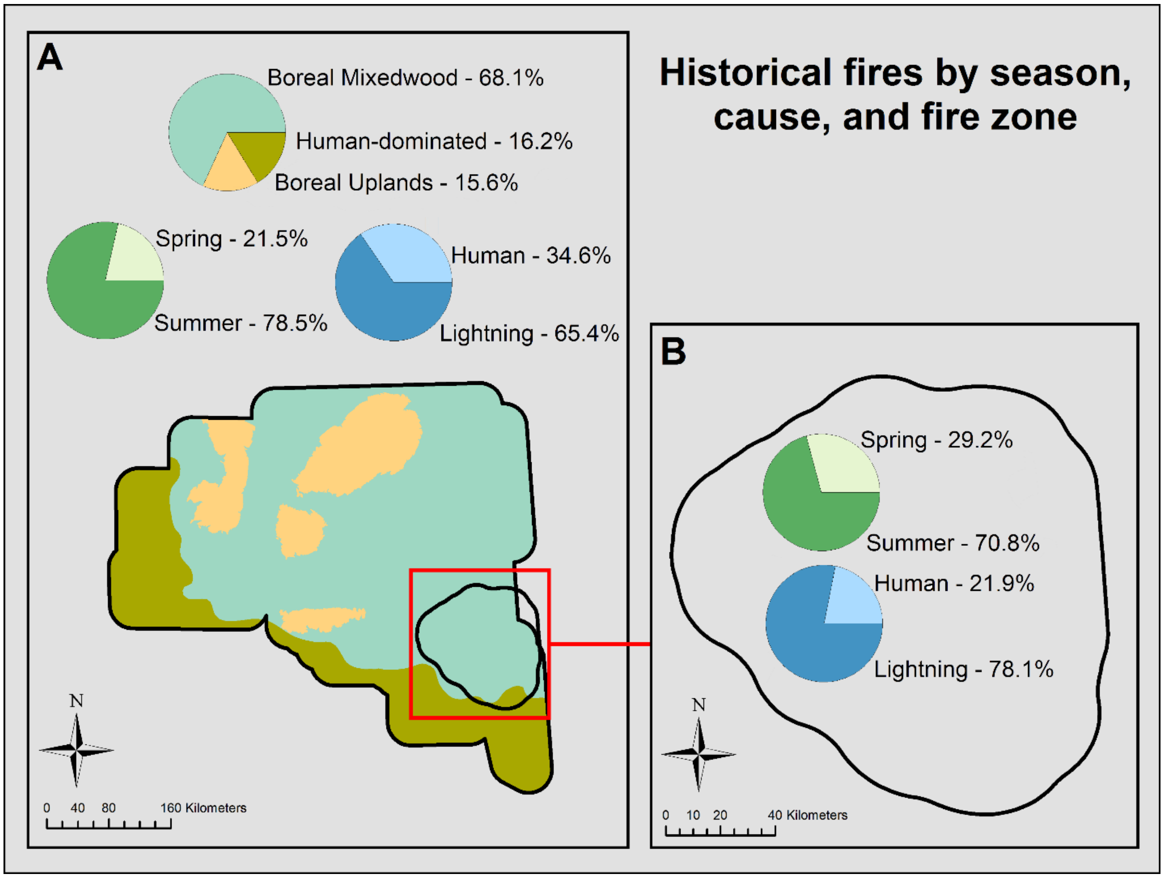

Figure 7: Grouping of historical fires by season, zone, and cause for the COSIA area (A) and the Cold Lake area (B).

Ignitions Module

Burn-P3 uses historical fire data to determine the number of fires modeled in each iteration. We used historical fire records for the study area (Natural Resources Canada 2018) to build a frequency distribution describing the number of fires per year within the study area (Figure 6). Burn-P3 uses this distribution to select the number of fires that grow to a minimum size of 200 ha after escaping initial suppression, or in the case of the Cold Lake area, a minimum size of 50 ha after escaping initial suppression.

The number of fires in each iteration is stratified by their cause and season based on historical fire data (Natural Resources Canada 2018). They are further stratified by the fire zone in which they are started (Figure 7). Each fire zone is governed by its own ignitions rules and fire weather, allowing Burn-P3 to simultaneously model fires in highly varied environments.

Ignition grids were used to provide spatially variable probabilities of fire starts. We determined that historical lightning-caused fires were randomly-located across the study area. Thus Burn-P3 assigned a random location (although stratified by fire zone) for all lightning-caused fires. However, human-caused fires were grouped in higher densities around transportation corridors and population centres. We used logistic regression analysis to generate ignition probability grids for human-caused fires. The dependent variable was a binary list of fire "presences", ignition locations for historical fires larger than 50 ha, and "absences", randomly-selected pixels that did not correspond with actual fire ignitions. Exploratory models showed that the predominant factor in human-caused fire likelihood was distance from roads, and that this effect declined exponentially with distance from the road. Therefore, ignition probability was modelled on the distance from the nearest road and the distance to the nearest population centre. We built a generalized linear model (R Development Core Team 2007), with the only significant variable being the cubic distance from the nearest road. We generated ignition grids based on this model using the "raster" package in R (Hijmans and van Etten 2012) (Figure 3).

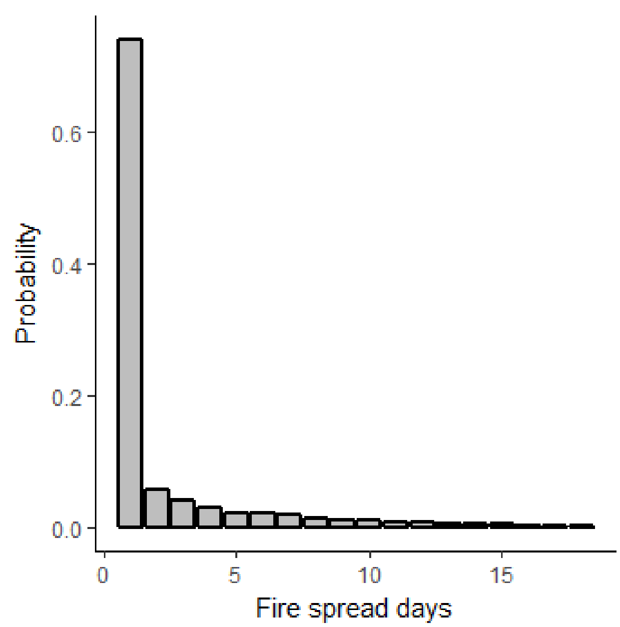

Figure 8: Distribution of the number of days of substantial fire growth for any fire in the COSIA and Cold Lake areas.

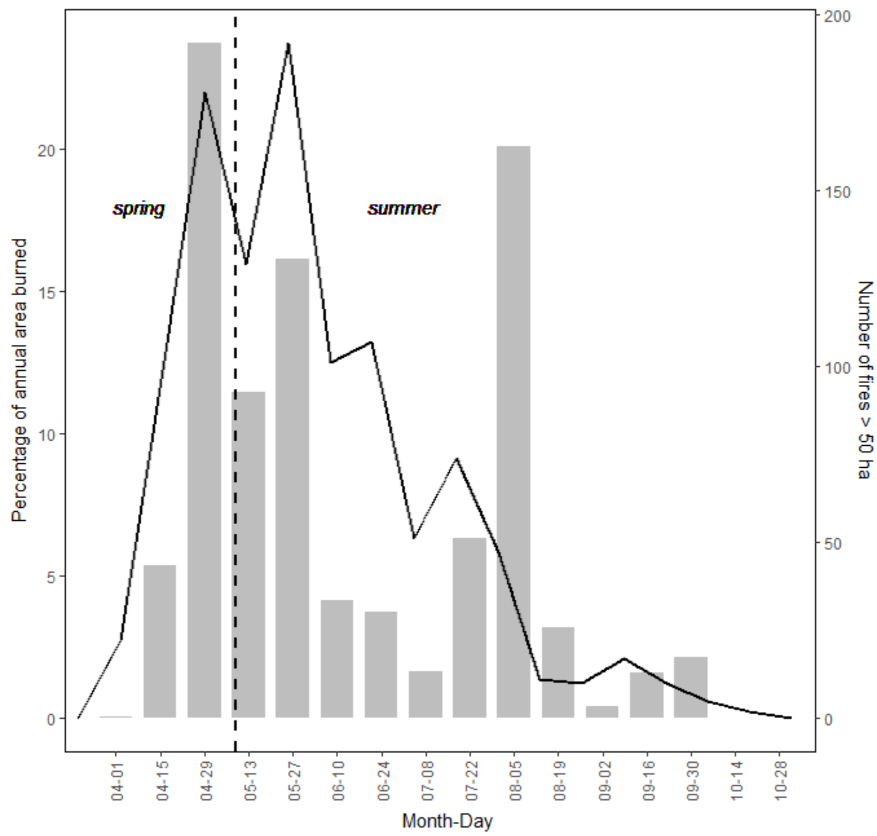

Figure 9: Number of historical fires > 50 ha and percentage of total area burned by two-week period for the COSIA area. Grey bars indicate area burned, solid black line indicates the number of fires, and the dotted vertical line indicates the boundary we chose to represent the shift from "spring" to "summer" fire conditions.

Spread days

Wildfires in the study area may remain active for weeks or even months, but most of their growth is limited to a few days (Parisien et al. 2005; Podur and Wotton 2011). Burn-P3 models these days of substantial spread (hereafter "spread days") and discards days where insignificant fire growth occurred. Spread-event days were based on a database of daily fire progression from satellite-detected hotspots beginning in 1994. A frequency distribution of the number of spread days was produced for the COSIA study area (Figure 8), which was also used for the Cold Lake area due to the limited number of large fires that have occurred in that area since 1994. This distribution was adjusted based on Burn-P3 outputs in order to produce a fire size distribution that was similar to the historical fire size distribution. This involved inflating the number of 1-day events (Figure 8), since satellite detection is biased towards detecting large, intense fires.

Fire weather

Daily weather conditions observed at noon were provided by Environment Canada and the Government of Alberta. We selected 13 stations with a minimum of 20 years of historical records to represent the COSIA area, and 7 stations to represent the Cold Lake area. We derived fire weather indices FWI) from these weather stations (Van Wagner 1987) using the "cffdrs" package in R (Wang *et al.*, 2017). FWI System variables were stratified by fire zone and season in which they occurred. Burn-P3 grows fires according to these observations, depending on the fire zone and season in which the fire occurred. Only days of significant fire spread are modelled in Burn-P3, therefore, only weather records conducive to fire growth were included in the final fire weather records. For this study, we defined these conditions as any day with a Fire Weather Index ≥ 18, based the threshold developed by Podur and Wotton (2011) but adjusted to accommodate smaller fires.

Other data inputs

Several additional data inputs included a shapefile of restored seismic lines, provided by COSIA members. These seismic lines represented the values against which wildfire risk was assessed.

Scenario development: Fuel and ignition treatments

After producing the baseline burn probability maps and some initial analysis, we held a workshop with interested stakeholders and project partners to develop scenarios to test different mitigation strategies (Table 4).

Table 4: Mitigation scenarios for testing changes to burn probability and associated fire behaviour metrics.

Scenario	Type	Intensity	Description
A	Baseline	n/a	
B	Ignition Management	Moderate	Zone 1: 97% Ignition Reduction.
C	Ignition Management	Low	Zone 2: 50% Ignition Reduction.
D	Ignition Management	High	Combined Ignition Reduction. (B+C)
E	Fuel Conversion	Low	Conversion to Deciduous (Low Intensity).
F	Fuel Conversion	High	Conversion to Deciduous (High Intensity)
G	Fuel Conversion	Low	Conversion to Grass (Low Intensity)
H	Fuel Conversion	High	Conversion to Grass (High Intensity)
I	Ignition Management and Fuel Conversion	High	High Bookend (D+F)
J	Ignition Management and Fuel Conversion	Low	Low Bookend (B+E)

- **Scenario A, Baseline:** Baseline scenario that represents current conditions as of 2017.
- **Scenario B, Ignition Management Moderate:** Designed to mimic the effect of changing social behavior around oil-and-gas facilities whereby ignitions are all but stamped out in the immediate vicinity of any oil-and-gas infrastructure. We buffered all o/g infrastructure by 500m and removed a few small isolated patches. Within this zone, we reduced ignition frequency by 97%, and readjusted the ignition frequency outside of this zone to ensure overall ignition reductions were achieved. See Figure 3.
- **Scenario C, Ignition Management Low:** Scenario designed to mimic the effect of oil-and-gas operators having their own firefighting resources that are dedicated to extinguishing fires occurring on the landscape covered by the oil sands lease sites. We arbitrarily chose a 50% effective suppression rate. As with scenario B we

readjusted ignition densities across the whole landscape to adjust for the removal of 50% of the ignitions in Zone 2 (see Figure 3).

- **Scenario D, Ignition Management High:** This scenario combines the ignition reductions of both Scenarios B and C.
- **Scenario E, Fuel Conversion (Conifer to Deciduous) Low:** This scenario mimics the effect of converting conifer stands within Zone 2 from coniferous fuels to deciduous fuels. We made an estimate of 2% of the coniferous landbase as the annual percentage harvested within the Alberta Pacific FMA assuming a 50 year rotation period. Within Zone 2, “harvest” was applied to C3 and C2 forested stands in order from the highest burn probability from the Scenario A. The harvest was assumed to be conducted over 5 years, so while it is at the AAC level, this scenario represents 5 years worth of cumulative harvest (5 AAC). “Harvested” areas were then replanted as deciduous (fuel type converted from C2/C3 to D1/D2)
- **Scenario F, Fuel Conversion (Conifer to Deciduous) High:** Same as Scenario E, but with harvest applied assuming a “surge cut” rate of 3X AAC, spread over 5 years (15 AAC).
- **Scenario G, , Fuel Conversion (Conifer to Grass) Low:** Same harvest rates as Scenario E, but recognizing that there is a delay in conversion from C2/C3 to D1/D2, immediately following harvest of C2/C3 fuel types, the fuel type is changed to O1 to reflect a temporary switch to flashy fuels like increased grass cover.
- **Scenario H, , Fuel Conversion (Conifer to Grass) High:** Same as scenario G, but related to Scenario F.
- **Scenario I, High Bookend:** Represents the “intensive management high bookend”. This combines the ignition reductions of Scenario D with the conversion of fuel types of Scenario F.
- **Scenario J, Low Bookend:** Represents “intensive management low bookend”. This combines the ignition reductions of Scenario B with the conversion of fuel types of Scenario E.

Analysis Methods: Processing Burn-P3 Outputs and Map Development

While Burn-P3 can produce numerous outputs, we only used the burn probability, fire size, and fire intensity outputs for both the COSIA and the Cold Lake landscapes. The burn probability of each cell (BP) is the number of times each cell burned (burn count) divided by 20,000 (the number of iterations). Maps of BP, and mean fire intensity were created for the COSIA and Cold Lake landscapes, and for all management scenarios. We calculated the change in BPs (∆BP) for each of the management scenarios by dividing the scenario BP by the baseline BP. We allowed a net change in BP of less than 20% either way (increase or decrease) to be considered "no change" due to the stochastic nature of the model.

We created fire hazard maps for all scenarios in the Cold Lake landscape by partitioning BP into 4 equal classes (dividing the maximum BP of the landscape by 4) and partitioning fire intensity into four classes which relate to distinct changes in fire behaviour according to the CFFDRS (Forestry Canada Fire Danger Group): <2,000 kW/m (surface fire); 2,000-4,000 kW/m (intermittent crown fire); 4,000-10,000 kW/m (continuous crown fire); >10,000 kW/m (extreme crown fire). We mapped fire hazard using a composite of these two variables both split into 4 classes to yield 16 distinct hazard classes of BP and fire intensity.

To identify the geographical source of the most damaging fires, we developed "firesheds". To do this we extracted the points representing the origin of each fire that burned in the simulation, and used the "Point Density" tool in ArcGIS to create a map showing the location density on the Cold Lake landscape. We then intersected the fire polygons created by Burn-P3 with the restored seismic lines to identify fires ("problem fires") that caused damage to the restored features. We then re-mapped the point density of these "problem fires" in three different ways: the density of points (all points treated as equal), the density of points weighted by the resulting size of the fire (problem fire density by size)), and the density of points weighted by the amount of restored seismic lines burned by each fire (problem fire density by damage).

To determine the effective area of the various treatment scenarios, we buffered the treated zones (either Zone 1 or Zone 2, depending on the scenario) at 1 km intervals to a distance of 30km from the treated zone. We then calculated the change in BP within each 1 km buffered strip as the scenario BP/baseline BP, and plotted the change in BP against distance from the treatment zone.

Results

The mean BP for the COSIA landscape was 0.009, which translates to a fire cycle of 110 years, however, the highest BP within the landscape was 0.0304 (fire cycle of 32.9 years). The highest BPs appear as the darkest shades of red in Figure 10A). It is apparent in the BP map that there are areas of reduced BP on the downwind (eastern) edge of lakes, rivers, and recent fires. Within the Cold Lake Caribou Range landscape (including the 25km buffer), the mean BP was 0.0153 (fire cycle of 65.4 years), and a highest value of 0.041 (24.4 year fire cycle) occurring in the northern portion of the area (Figure 10B). While this maximum value in the Cold Lake area exceeds the maximum value observed for the larger COSIA area, BPs should be interpreted in a relative sense, noting how much more likely one area is to burn than another. The spatial pattern of relative BP within the Cold Lake area are consistent between the COSIA and Cold Lake areas.

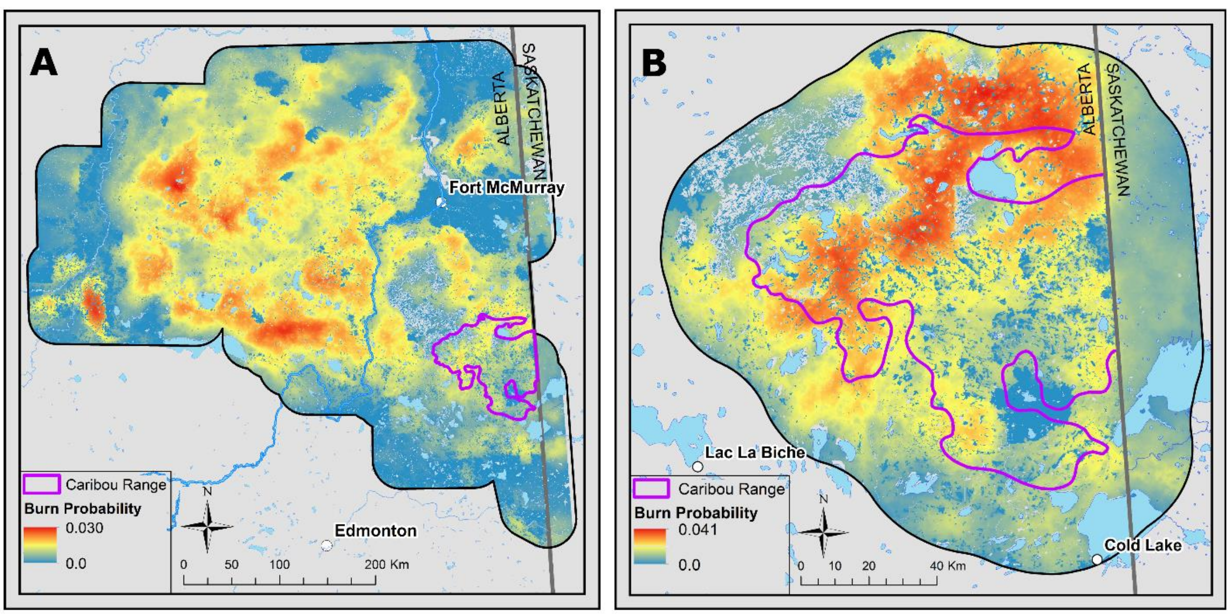

Figure 10: Burn probability surfaces for the entire COSIA study region (A) and the Cold Lake Caribou Range (B, both including the 25 km buffer). The Cold Lake Caribou Range burn probability map is from a separate model run, not just a clipped out area from the larger landscape. Also note: the colour stretches for each map are at different scales.

The changes to the mean BP of the landscape are shown in Table 5, and the spatial pattern of these changes in all but scenarios G and H (short term conversion to grass in the harvest scenarios) are shown in Figure 11. There were significant decreases in overall BPassociated with increasing intensity of both ignition suppression and harvest intensity, but the high bookend management scenario (Scenario I) showed less overall reduction in BP than the low bookend scenario (Scenario J). It is apparent from Figure 11 (panels E and H), however, that the high management bookend had a much larger effect on a smaller part of the landbase, and the overall higher level of reduction in the low bookend is the result of stochasticity in the model. The effective area of burn probability reduction was largely restricted to within 10km of the treatment zones in both the of the bookend scenarios (I and J, see Figure 12). Regarding fire hazard (Figure 13) we can see that the largest reductions are observed in the High Bookend scenario (I). Most of the reductions occur within the treatment areas (Zone 1 and Zone 2).

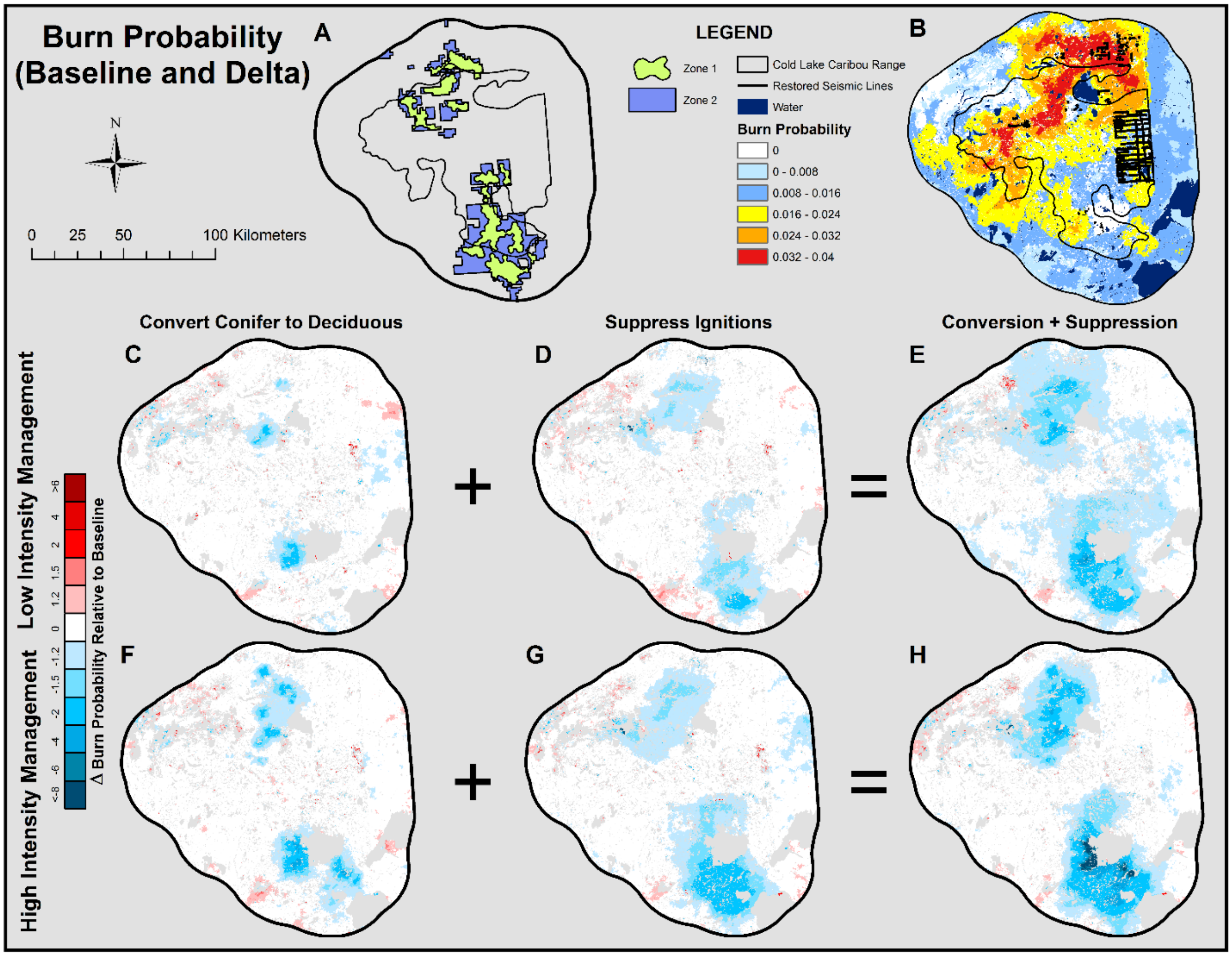

Figure 11: Burn probability and changes in burn probability in the Cold Lake area. Panel A: the burn probability mitigation zones are shown (the areas in which the various treatment scenarios are applied). Panel B: Baseline model scenario burn probability, also showing the location of the restored seismic lines. Panels C-H: Differences in burn probability between the various scenarios and the baseline (Scenario Burn Probability/Baseline Burn Probability). Shades of blue indicate reductions in burn probability relative to the baseline, shades of white indicate no difference (within a 20% tolerance), and shades of red show increases in burn probability relative to the baseline. Panel C = Scenario E, Panel D = Scenario B, Panel E = Scenario J, Panel F = Scenario F, Panel G = Scenario D, and Panel H = Scenario I.

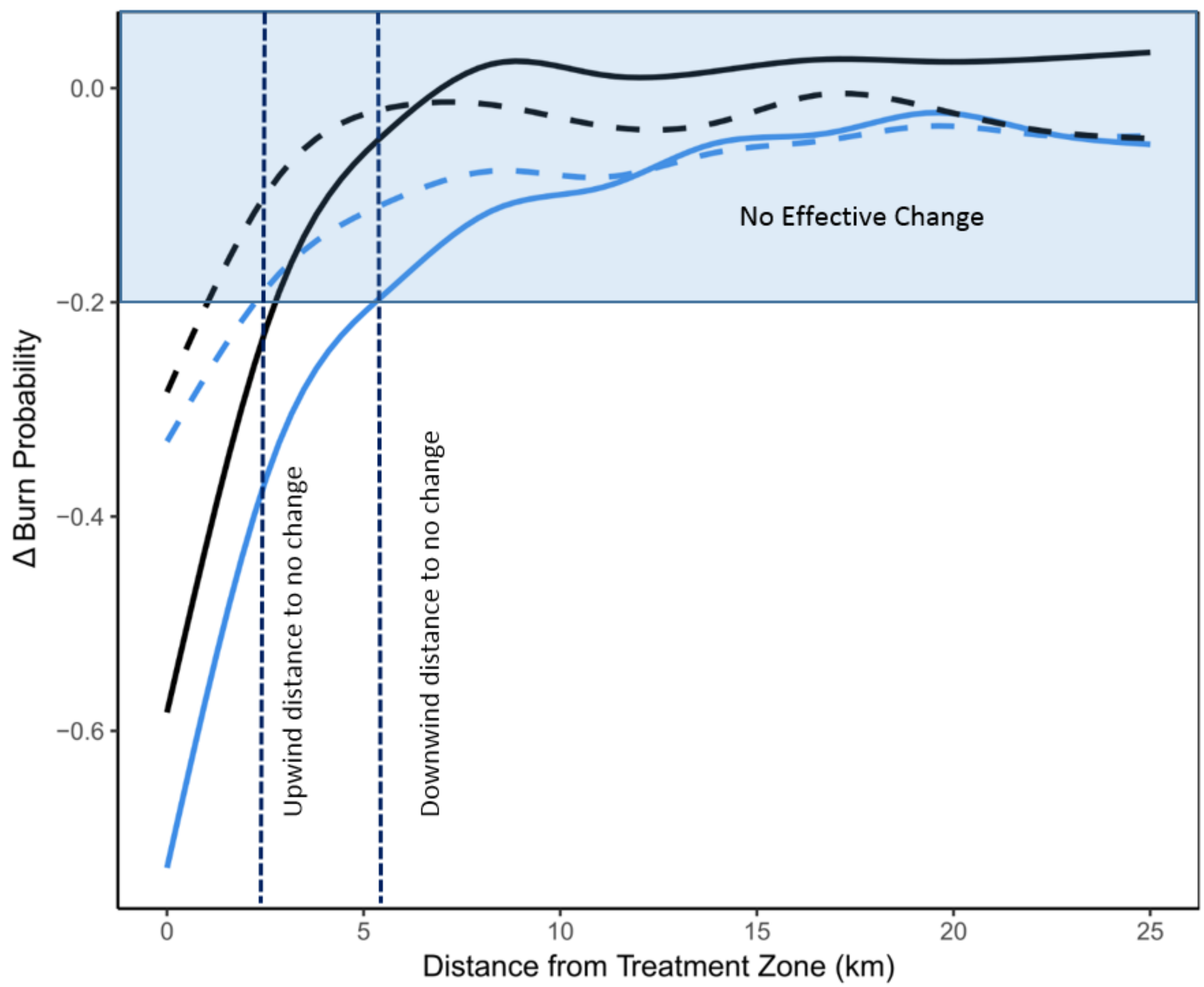

Figure 12: Change in burn probability relative to the baseline due to treatments declines as the distance from the treatment zone increases. The blue band represents the zone of no effective change (less then 20% difference in BP due to treatment). Blue lines indicate the High Bookend Scenario (I) and black lines indicate the Low Bookend Scenario (J). Solid lines indicate the downwind side of the treatment zone, and dotted lines indicate the upwind side. The vertical dotted lines (drawn for the High Bookend only) indicate the distance from the treatment zone at which the treatments have no effect on BP.

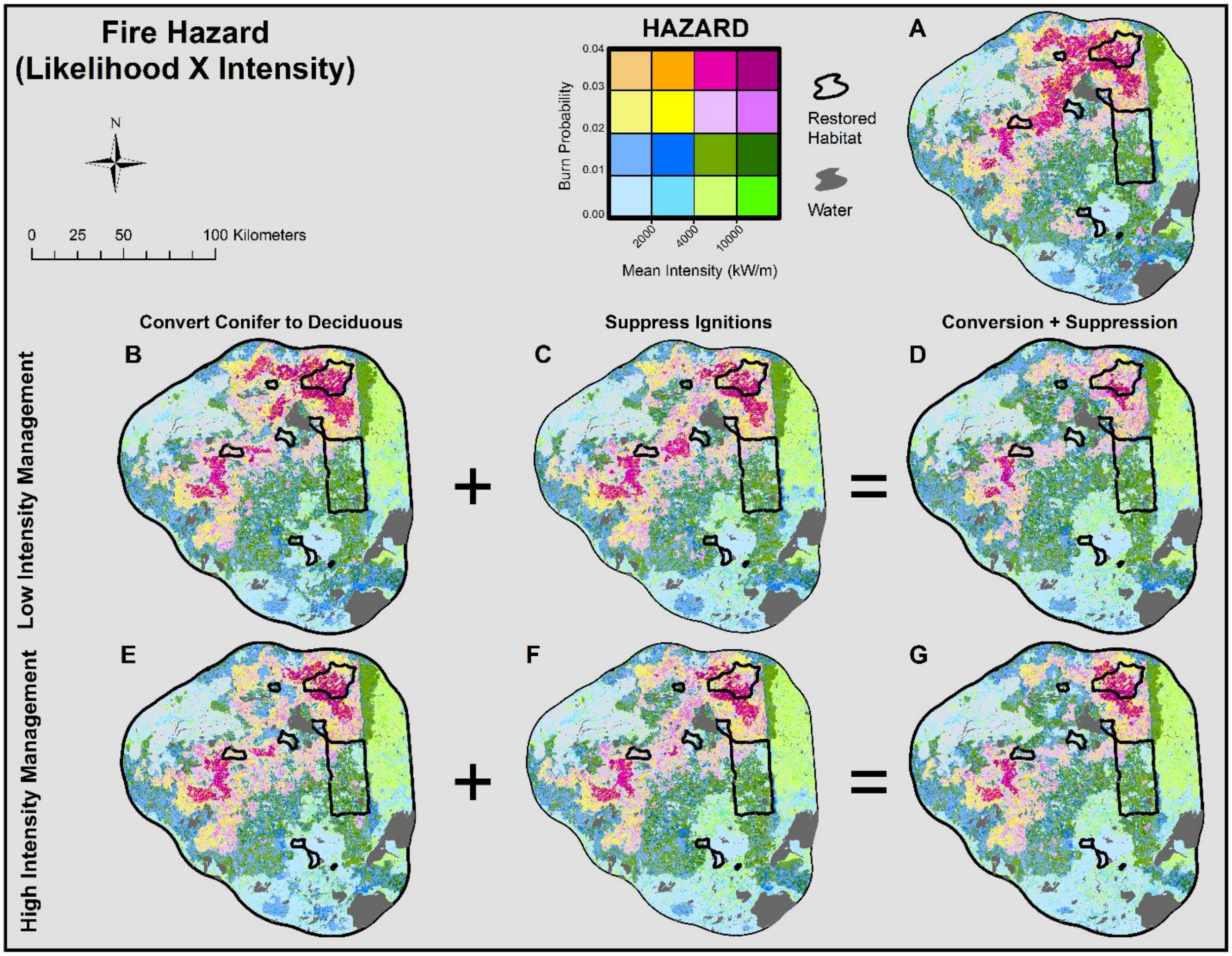

Figure 13: Fire hazard in the baseline and mitigation scenarios. Panel A: Baseline model scenario fire hazard, also showing the location of the zones where seismic lies have been restored. Panels B-G: Wildfire hazard for each scenario. Panel B = Scenario E, Panel C = Scenario B, Panel D = Scenario J, Panel E = Scenario F, Panel F = Scenario D, and Panel G = Scenario I.

We constructed firesheds in three different ways: A) by density of fire start locations where the fires burned into the restored seismic lines ("Problem Fires", Figure 14 (B, C, and D); B) by density of problem fires, weighted by how big the fires grew to (Figure 14 (E, F, and G); and C) by density of problem fires weighted by how much damage each fire caused (length of seismic lines burned, Figure 14 (H, I, and J). What this reveals is that most fires that caused damage to the restored seismic lines originated within the immediate area of the seismic lines (the "local effect"), and that when these fires are weighted by how much damage is caused, the local effect is exaggerated even more.

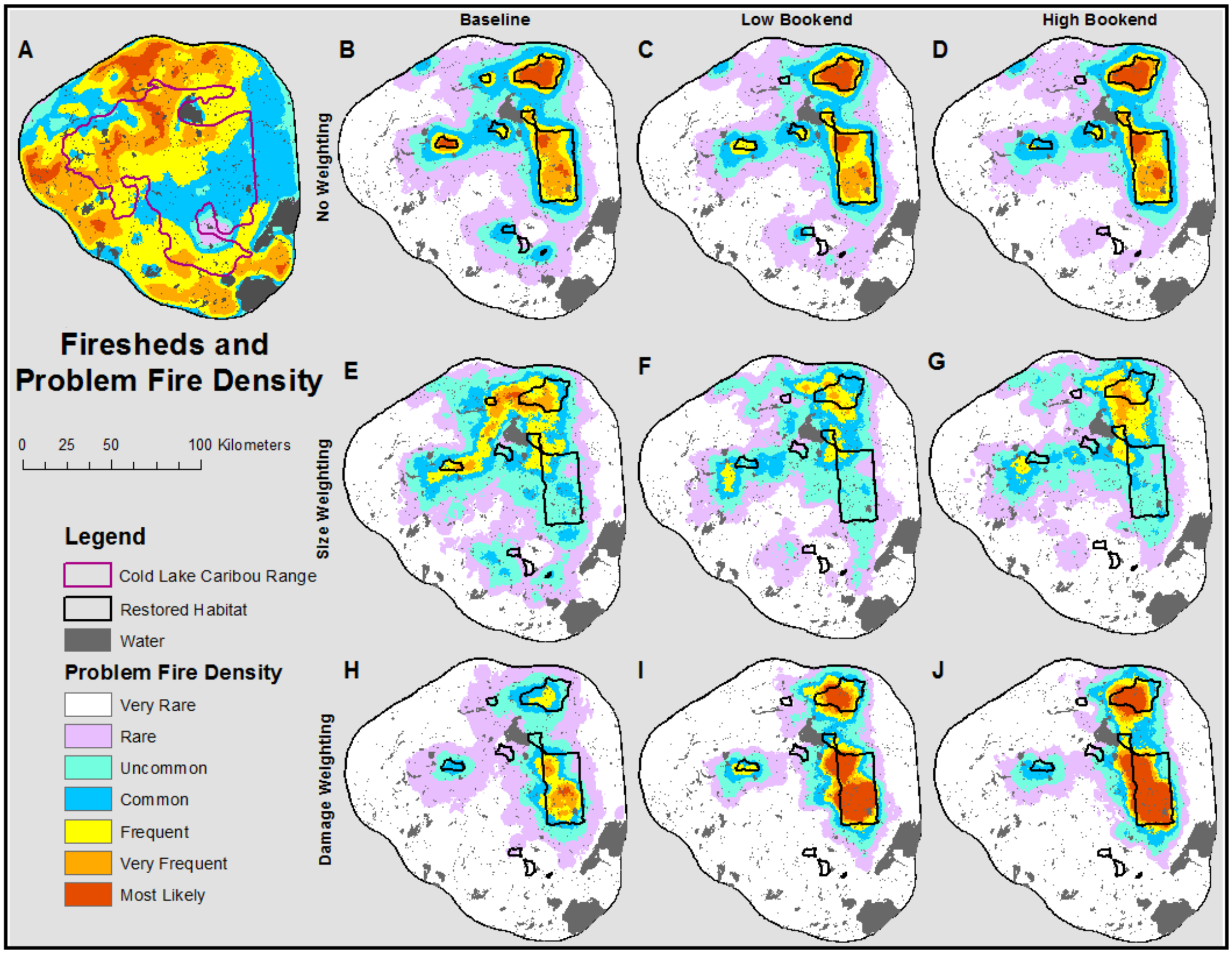

Figure 14: Panel A shows the density of all modeled fire origin points from the Cold Lake Caribou Range baseline scenario. Columns represent scenarios (Panels B, E and H are Baseline, Panels C, F and I are Low Bookend, Panels D, G and J are High Bookend). The first row (Panels B, C, and D) represents density of ignition points for fires that burn into the restored seismic lines ("Problem Fires"). The second row (Panels E, F, and G) show the density of problem fire start locations weighted by the eventual size of the fire. The third row (Panels H, I, and J) show the density of problem fire start locations weighted by the length of seismic lines burned.

Table 5: Mean burn probability for the whole landscape in the baseline and different management scenarios. These values are shown for the whole modeling area (Cold Lake + 25km buffer zone)

Scenario	Cold Lake + 25km Buffer Zone	Cold Lake Caribou Range	Restored Habitat Zone
A. Baseline	0.0153	0.0175	0.0178
B. Zone 1 Ignition Reduction	0.0146 (-4.3%)	0.0165 (-6.2%)	0.0170 (-4.7%)
C. Zone 2 Ignition Reduction	0.0142 (-7.4%)	0.0159 (-9.1%)	0.0168 (-5.6%)
D. Combined Ignition Reduction	0.0137 (-10.1%)	0.0153 (-12.7%)	0.0164 (-8.1%)
E. Conversion to Deciduous Low	.0149 (-2.8%)	0.0163 (-7.0%)	0.0177 (-0.5%)
F. Conversion to Deciduous High	0.0144 (-5.5%)	0.0161 (-8.2%)	0.0171 (-3.8%)
G. Conversion to Grass Low	0.0151 (-1.0%)	0.0170 (-3.0%)	0.0181 (+1.9%)
H. Conversion to Grass High	0.0150 (-1.8%)	0.0171 (-2.7%)	0.0173 (-3.1%)
I. High Bookend	0.0130 (-14.9%)	0.0130 (-21.2%)	0.0162 (-8.8%)
J. Low Bookend	0.0124 (-18.6%)	0.0135 (-23.2%)	0.0147 (-17.6%)

Discussion

This study was intended to A) identify the current wildfire hazard throughout the greater COSIA landscape and within the Cold Lake Caribou Range; B) use these findings to devise mitigation scenarios; and C) model the effect that the chosen mitigation efforts would have on wildfire hazard. In our assessment of the current wildfire hazard, we found that recent large burns and waterbodies provided “shields” that reduced burn probability on their leeward sides (to the east), which is consistent with the findings of (Erni et al. 2018). Using this information, we opted to concentrate conceptual mitigation activities in specific parts of the landscape in order to mimic the shielding effect of waterbodies and large recent burns (Parisien et al. 2008). As the landscape is highly industrialized, we chose to use parts of the landscape under active industrial management as “intensive management zones” within which we could focus mitigation efforts and determine the effects of large-scale conversion of coniferous forests to deciduous and reductions of potential ignitions on the BP of leeward restored caribou habitat zones. These intensive management zones were indeed effective at reducing BP and wildfire hazard. Assuming that the fuel changes caused by silvicultural species conversion would last for many decades, this reduction in hazard would be effective for a considerable period of time.

We did find, however, that the effectiveness of these treatments declined rapidly as distance from the treatment zones increased. In general, the effectiveness of any mitigation measures is fairly localized (within 5km).

While recent wildfires are effective at restricting future ignitions within the area burned (and thereby reducing future burn probability in adjacent locations), this phenomenon is short-lived. Studies have shown the reburn potential of sites can be reduced for several years, depending upon the location and severity of the previous fire (Héon et al. 2014; Parks et al. 2016; Beverly 2017). In the Alberta boreal forest, with prevailing winds driving fires primarily in an eastern direction, the best place to establish conservation measures (breeding pens, predator exclosures, restoration of seismic lines) would be on the leeward (eastern) side of recent burns. This sheltering effect is temporary, however, because as vegetation regrows on the site, and as standing dead timber falls down to contribute to the surface fuel loading of a site, the reburn potential rises and returns to the pre-BP within a few years. Therefore, it is important to have redundancy and flexibility in these conservation measures to take advantage of new fire disturbances and recognizing the temporally-limited nature of the protection afforded by old fires. Using waterbodies as "shields" would be advantageous, as these are more or less permanent features of the landscape, and provide protection for a much longer period of time. Furthermore, under extreme fire weather conditions, virtually no fuel treatment or sheltering waterbody/burn will have any effect on reducing BP.

Managers are not limited to using only "natural" barriers to fire spread to attempt to reduce risk to specific values. Numerous methods of "manufacturing" reduced fire risk are possible, ranging from modifying vegetation (changing the fuel type) to affecting ignition likelihood on the landscape (Agee et al. 2000). Although there exists numerous methods of fuel treatment, we opted to test the efficacy of harvesting coniferous stands and converting them to deciduous stands. This treatment represented the most realistic and economically feasible management scenario given that the industrial management zones surrounding and within the Cold Lake Caribou Range are located within the Alberta-Pacific Forest Management Unit. The rationale behind the ignitions reduction scenarios represented the concept of instituting strong ignition prevention strategies surrounding industrial facilities (Zone 1 restrictions) such as limited all-terrain vehicle (ATV) use, smoking bans, and general elevated risk-reduction education programs. Complete elimination of ignitions was considered unrealistic, thus we chose a 97% reduction in human caused fires. The Zone 2 50% ignition reduction scenario imitated the effect of oil-and-gas companies hiring dedicated wildfire suppression staff, which would increase the effectiveness of overall suppression efforts within the Zone 2 landscape.

The effectiveness of these mitigation measures appears to be concentrated to a maximum distance of 5 km from the treatment zone. To protect caribou conservation measures, the treatments themselves need to occur in relatively close proximity to the area to be protected. The reason that recent wildfires show stronger shielding effects than these fuel treatments and suppressed ignitions is that the wildfires (in the boreal) tend to affect the vast majority of the fuels within their perimeter. These management scenarios are only able to affect a significantly smaller proportion of the landscape, making the "shield" more like a mesh, with many holes in it that still allow fire to move across the landscape. However, a further advantage to mitigation options such as the ones tested here is that managers can choose when and where to apply timber harvesting, fire suppression, and even ignite prescribed burns.

If fire-fighting resources were unlimited, and timber harvesting rules flexible enough to allow for much larger areas to be harvested, it would be theoretically possible to achieve the same level of protection afforded by recent burns. However, while suppression may be realistic on small parts of the landscape such as the treatment zones identified in our scenarios, the relatively localized effect suggests it is a good idea to have numerous treatment zones and fully evaluate the multiple options for optimal placement. While harvesting ever larger areas to reduce flammable coniferous fuels would be an effective treatment, one has to consider the trade-offs related to the ecological integrity of the landscape.

This modeling exercise showed that the majority of the wildfire-induced damage to the restored seismic lines came from fires igniting close to, or within the restored habitat zone. While some of the potential damage appears to come from large fires igniting at considerable distance from the restored lines, these larger fires tend to burn under conditions that do not lend themselves to effective suppression activities. As evidenced by recent events such as the fire in Fort McMurray, fires that originate at considerable distance from a value at risk can burn massive areas of the landscape, and will burn through virtually all vegetation types. Our analysis of the firesheds associated with these treatments revealed that highly damaging fires can originate virtually anywhere on the landscape if the conditions are severe, however mitigation treatments do indeed have strong effects on less than severe fire events. Some degree of loss has to be factored in to conservation management planning as the largest wildfires burn under conditions that treat virtually all fuel types as burnable. As stated above, redundancy in conservation projects scattered across a broad landscape is the only true insurance against losses to wildfire.

Several factors limited our ability to test a thorough list of mitigation options. We did not have timber harvest plans from the local operators, which would have allowed us to evaluate the effect of the actual harvest plans. We had to rank harvesting priority based on the burn probability of stands, but this did not factor in the merchantability of the forest stands. Further exploration wherein different criteria and patterns to select treatment locations could be used to increase the efficacy of mitigation options. We also could improve confidence in these model runs if we had better fuels inventories. There was a clear boundary effect at the Saskatchewan border, as the agencies responsible for developing vegetation inventories and fuel grids on either side of the border clearly have different methods and criteria.

In conclusion, the main focus of this study to was to examine fire hazard and fire effects on vegetation throughout the COSIA and Cold Lake areas. While we were interested in these factors as they relate to caribou conservation, the methods employed here are broadly transferable to any conservation considerations or place-based value at risk such as the wildland urban interface. From the perspective of caribou habitat, wherever peatlands are burned there is a loss of high quality caribou habitat. So long as multiple areas are chosen to focus conservation measures, rather than a single large reserve, there should be considerable redundancy in high quality caribou habitat so that the loss of any one area due to wildfire does not destroy all such areas. Targeted conversion of coniferous forests to deciduous forests was shown to be an effective way to reduce wildland fire risk, however, this is a slow process given the allowable rates of timber harvesting in the region. Furthermore, reducing the number of fires through ignition prevention and enhanced suppression can also have beneficial effects if carefully applied.

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Appendix A - Future Burn Probability Analysis

Climate change over the next century will impact wildfire frequency and annual area burned as temperatures rise and extended droughts become more common, potentially impacting boreal woodland caribou (*Rangifer tarandus caribou*) herds in the COSIA study area. For example, Flannigan et al. (2005) project possible increases of 74-118% in annual area burned by 2100, and Boulanger et al. (2014) report an increase of 370% in modeled area burned with a 300% increase in number of fires by 2100. Changes in the climate are driving an increase in fire-conducive weather, but also a lengthening fire season (Albert-Green et al. 2013; Magnussen and Taylor 2012), though the projected magnitude of change is highly uncertain.

Weather and climate are the primary drivers of fuel moisture, fire spread, and lightning ignitions. Furthermore, long-term climatic trends determine vegetation cover type on the landscape. These factors may interact to drive a systemic shift in fuel characteristics and overall fire regime. For example, in the boreal forest of North America, an increasing abundance of deciduous species could decrease fire frequency; conversely, the expansion of grasslands could increase the frequency of spring grass fires. Wang et al. (2016) evaluated future burn probability in central B.C., and found that while more fire-conducive weather would lead to better conditions for fire ignition and spread, climatic changes would also promote vegetation types that are substantially less flammable than the current vegetation. Stralberg et al. (2018), however, show that vegetation changes in the COSIA study area are unlikely to result in greatly reduced flammability.

The aim of this exploration is to assess how projected climate change may affect the burn probability of the study area over the next century. Specifically, we evaluate the impacts of climate change on two major factors controlling future fire likelihood: fire-conducive weather and flammable vegetation (i.e., fuels). We evaluate future burn probability by comparing the present-day burn probability generated by this study to modeling projections produced for the province of Alberta under future climate conditions.

Methods

Burn probability projections

Future projections of burn probability in the study area were based on previous research published in the peer-reviewed literature. We estimated future burn probability through the 2050s and 2080s under the representative concentration pathway (RCP) 8.5 scenario (IPCC 2013) for three general circulation models (GCMs): UKMO-HadGEM2, CSIRO-Mk3, and CanESM2. This RCP 8.5 scenario assumes that greenhouse gas emissions are not successfully curtailed through international efforts. These maps provide an estimate of the change in burn probability across the COSIA area and the resulting impact on the fire regime of each caribou range within the COSIA study area. These projects assume that suppression efforts remain similar to baseline levels and that vegetation type remains roughly similar to modern conditions.

We modeled future burn probability in several steps:

1) Burn probability was modeled under current conditions using the Government of Alberta (GoA) observed fuel grid using Burn-P3, as presented in the main body of this report.
2) Projections from Stralberg et al. (2018) were used to calculate burn probability in the 2050s (2041-2070) and 2080s (2071-2100) by extrapolating escaped fire rates, fire weather, and spread-event days to the future climate conditions, as developed by Wang et al. (2015). These burn probability surfaces used a modeled fuel grid, based on climate, geology, and topography.
3) Burn probability outputs for the COSIA area were extracted from the model results and converted to delta burn probability maps. Delta burn probability maps represent a change in burn probability as a ratio, and are calculated by dividing one burn probability raster by the other. The resulting maps show the degree of change between the modeled baseline (the modern conditions) and the two future periods (baseline to 2050s, baseline to 2080s).
4) Delta burn probability maps were multiplied by the modern burn probability surface based on the GoA fuel grid for the 2050s and the 2080s. This was done in order to

estimate future burn probability based on an observed fuel grid, instead of the modeled fuel grid used in Stralberg et al. (2018).

Vegetation cover projections

We projected future changes in vegetation cover as driven by climate change and modeled wildfire, as per Stralberg et al. (2018). Vegetation cover was predicted for the 2050s and 2080s using "Random Forests", a machine learning algorithm (Breiman 2001). The Random Forest was trained on observed vegetation cover under modern conditions, and changes to vegetation cover were based on projected climate change (UKMO-HadGEM2, CSIRO-Mk3, and CanESM2 GCMs) and topoedaphic factors, including geology, terrain, and mapped wetland class. We visualized these vegetation cover projections as six general vegetation cover types: spruce, pine, mixedwood, deciduous, bogs/fens, and grassland.

Results and discussion

Mean annual burn probability for the COSIA study area increases from approximately 0.91% to 2.24% in the 2050s and 3.50% in the 2080s (Table A1, Figure A1), based on a mean of the three GCMs. The mean annual modeled area burned is 179,000 ha for the baseline period, 442,000 ha for the 2050s, and 690,000 ha for the 2080s, out of a total area of 19,715,000 ha. Burn probability increases are greatest in the southwest of the COSIA study area along the boreal-parkland boundary. There are increases in burn probability in all caribou ranges, with a maximum burn probability of 5.17% for the WSAR and Red Earth herds by the 2080s (Table A1).

Table A1: Estimated mean future burn probability (BP; %) for the caribou herd ranges within the COSIA area. WSAR = Western-side Athabasca River. ESAR = East Side Athabasca River.

Climate scenario	Mean BP	BP - WSAR	BP - ESAR	BP - Cold Lake	BP - Red Earth	BP - Richardson	BP - Nipisi	BP - Slave Lake	BP - Chinchaga
Baseline	0.91	1.49	0.94	0.85	1.49	0.94	0.85	1.13	0.85
2050s	2.24	3.32	2.15	2.04	3.32	2.15	2.04	2.74	2.04
2080s	3.50	5.17	3.22	3.15	5.17	3.22	3.15	4.27	3.15

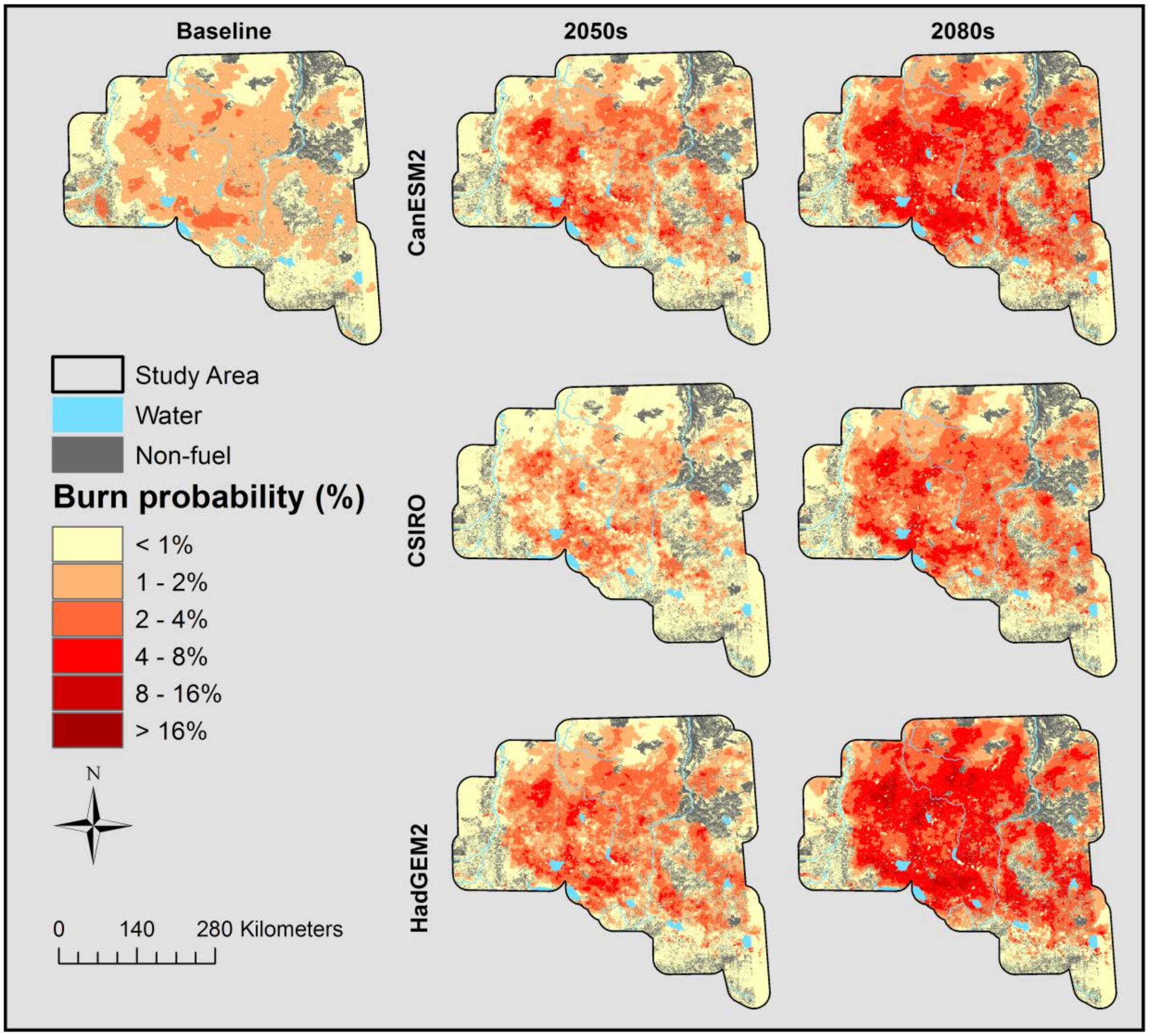

Figure A1: Estimated baseline and future burn probability (BP; %) for the COSIA area for two time periods, based on a transformation of the baseline BP, and presented for three GCMs.

Modeled future climate conditions produces a sharp increase in projected frequency of large fires per year (Figure A2). The frequency of fires > 100,000 ha consistently increases from ~ 1 per year to at least 9 per year within the COSIA study area by the 2080s, with considerable variability between the three GCMs (HadGEM2 model projecting approximately 35 fires > 100,000 ha per year). While the results from the HadGEM2 model seem severe, even the most conservative model predicts a large increase in the number of large fires as a result of climate change.

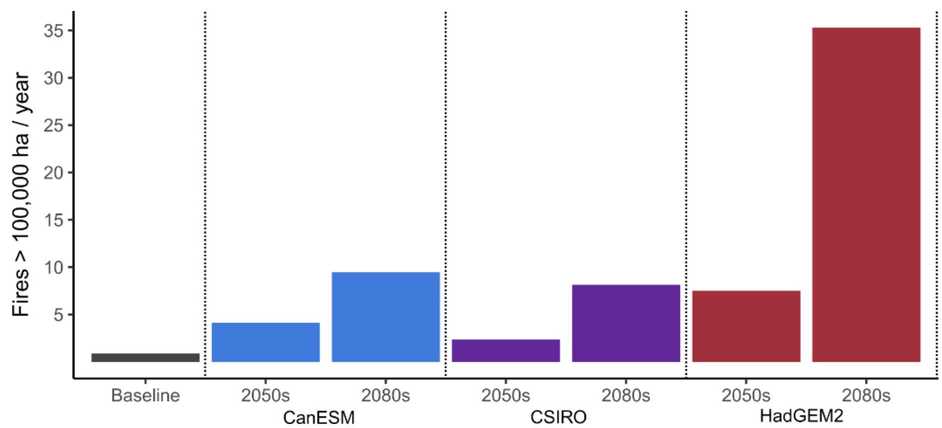

Figure A2: Number of modeled fires larger than 100,000 ha, per year, within the COSIA area for each GCM considered.

Increasing landscape burn probability will have consequences for the present-day caribou herd ranges. These ranges are likely to experience shortened fire cycles (the number of years required to burn an area equal to the size of a specified area), from a range of 67 - 117 years under modern conditions to a range of 19 - 32 years by the 2080s (Figure A3). Burn probability across these ranges will not be uniform, however, with some areas burning more frequently than others (Figure 2A). Boreal fire history shows that peatlands are not significantly protected from fire relative to uplands, especially in areas of frequent droughts, such as the study area (Turetsky et al. 2004). For this reason, caribou habitat is not sheltered from increasing fire frequency by virtue of being centered in wetlands.

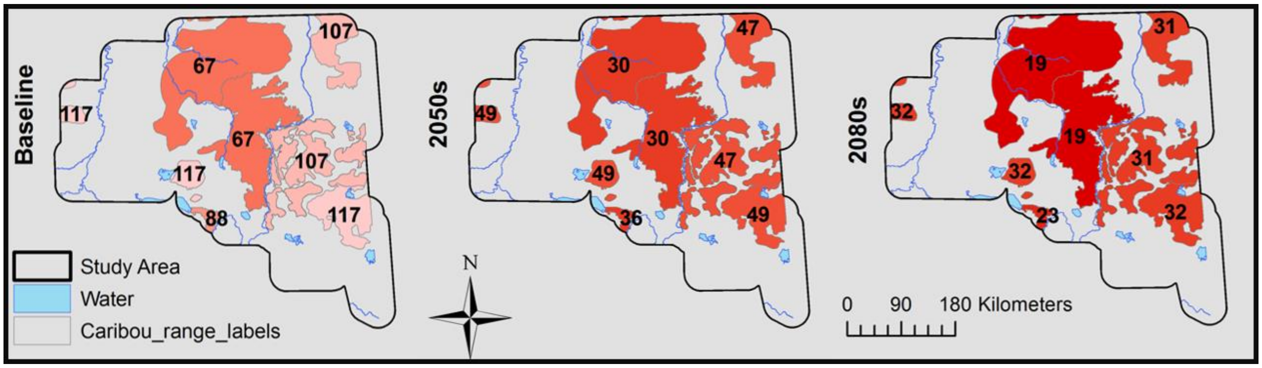

Figure A3: modeled fire cycle (years) of specific caribou herd ranges, taken as the average of the three GCMs. Fire cycle is defined as the number of years required to burn the number of hectares equal to the size of the study area.

Due to the stochastic nature of fire, a single large fire or several fires in a close succession of years could erase large swaths of critical caribou peatland habitat in a short time. Furthermore, increased area burned will decrease the average forest age as burned area regenerates. Young forests provide less cover for caribou than mature forests, and are favorable habitat for white-tailed deer (*Odocoileus virginianus)* (Côté et al. 2004) and moose (*Alces alces*). Large populations of white-tailed deer and moose increases caribou's risk of predation from gray wolves (*Canis lupus)* through incidental predation (Latham et al. 2011), further raising predation pressure on caribou even if critical peatland habitats are spared from wildfire. For this reason, conservation efforts may have to dynamically account for the changing nature of fire and changing vegetation patterns if they are to remain effective through the 2100s. Ideally, caribou populations could be stabilized before the effects of increasing wildfire frequency are realized.

Vegetation cover changes will have complex and uncertain effects on the ecology of the boreal forest. We predict that mixedwood forests and spruce/pine forests may largely be replaced by deciduous forests and grasslands by the end of the current century (Figure A4). These changes are likely to compound caribou predation risk, given that white-tailed deer will benefit from the expansion of grasslands (Côté et al. 2004). Also, fire return intervals in grasslands tend to be considerably shorter than forests, given that grasses are able to regrow rapidly after burning, thereby causing a major transformation in fire-vegetation dynamics. Conversely, forests may have significantly longer fire return intervals than grasslands, since forest regeneration takes at least a decade, a period during which little wildfire activity is common. These changes do not necessarily preclude healthy caribou herds in the study area; holdout bogs and fens may be the key to caribou habitat conservation, and similarly mature conifer forests may persist in many areas, provided they do not burn frequently or at high intensity.

Modeled vegetation cover changes are based on two key assumptions: that fens and bogs would persist until at least 2100 and that post-fire vegetation regeneration would be determined by climate and topoedaphic characteristics. These assumptions are useful for modeling purposes and are based in reality (Waddington et al. 2015; Whitman et al. 2018), although some shallow fens and bogs may convert to other vegetation types if fire is follows severe drought (Kettridge et al. 2015). More importantly, post-fire vegetation succession is complex, often depending on fire severity and pre-fire community composition (Whitman et al. 2018), which are not accounted for in our projections. Therefore, vegetation cover change by 2100 will likely be less extreme than shown here (Figure A4).

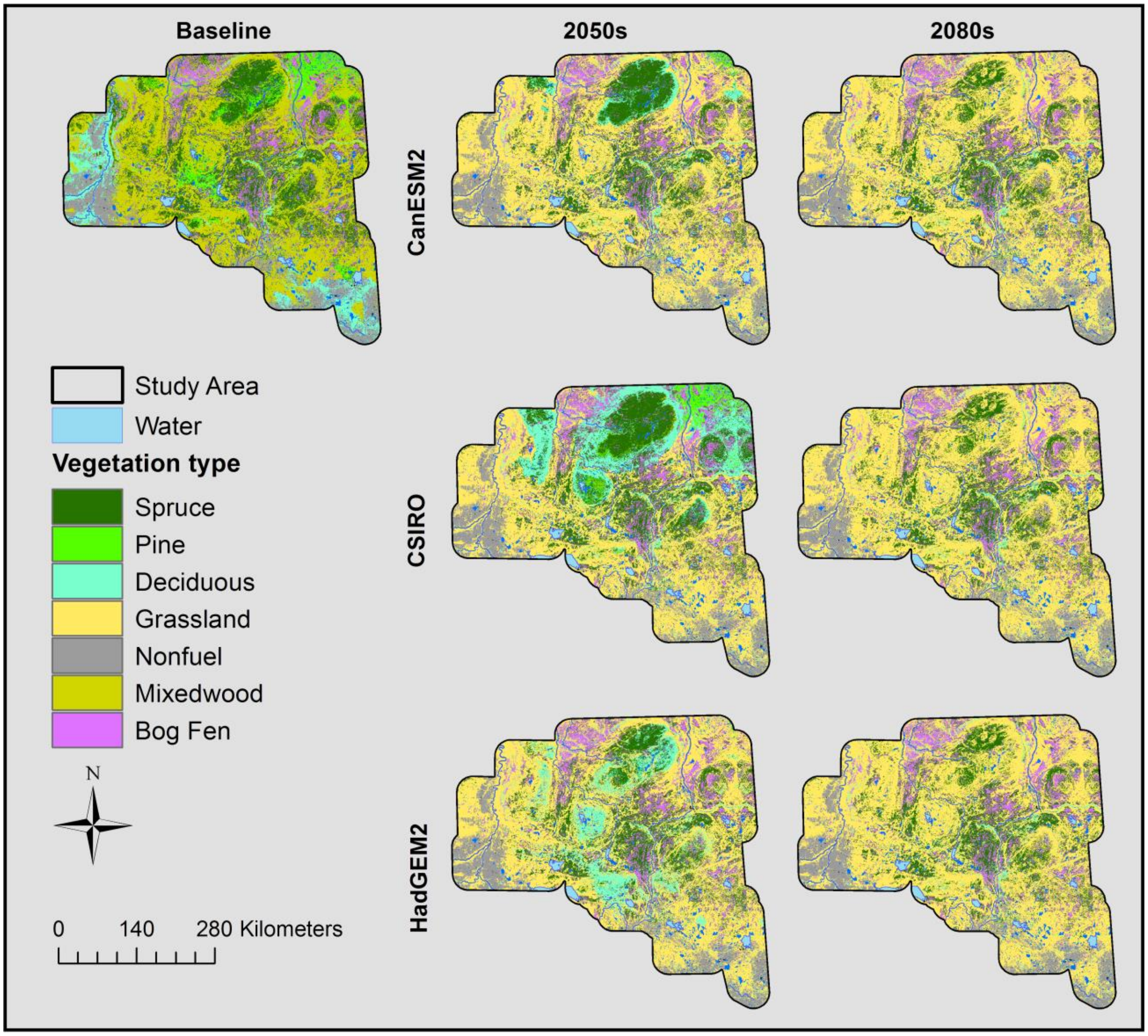

Figure A4: Modeled vegetation cover for the 2050s and 2080s based on climate and topo-edaphic factors, presented for three GCMs.

Limitations

Modeling studies face the potential problem of extrapolation of relationships beyond the range of observed values, which adds substantial uncertainty to model projections. For example, it is highly uncertain how wildfire activity will respond to changes in vegetation in the study area, especially if the already-intense fire suppression policies are maintained or expanded. Changing climate will introduce immigrant non-native species, which will lead to no-analogue vegetation assemblages (i.e., groups of species that are not represented in the historical record). These changes will impact burn probability in an unpredictable manner;

however, while the magnitude of the burn probability changes, the positive trend is in agreement with published literature: a greater frequency of hot and dry weather conditions will invariably increase fire activity, provided that sufficient fuels are available.

Our future burn probability surfaces were impacted by the state of forest fuels in the present day, which had the practical effect of limiting burn probability in recent fire perimeters, such as the Horse River Wildfire near Fort McMurray. These areas were classified as “vegetated non-fuel” in our original fuels map, since they were unlikely to burn within 5 or 6 years of the previous fires (Krawchuk and Cumming 2011). These areas will likely regenerate to forest by the 2050s and 2080s, although their low burn probability in the baseline period has been unrealistically propagated to our 2050s and 2080s burn probability maps. Therefore, the burn probability in these areas will almost certainly be higher than indicated on our maps.

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