SCIENTIFIC LITERATURE REVIEW: PHASE 1

JUNE 13, 2018

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IN FULLFILLMENT OF CONTRACT # SC456069

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EXECUTIVE SUMMARY

Shifting Mosaics Consulting (SMC) was hired to conduct Phase 1 of a high-level literature review on the topic of prescribed fire in the Northwest Territories (NWT) adjacent to a community to convert conifer forest to deciduous forest with key words including the interaction between prescribed fire and stand conversion, permafrost, climate change, ignition prescriptions, high northern latitude, resiliency of forests, and wildlife (i.e. caribou, moose, bison, and fur-bearers).

This first approximation provides the Government of the NWT (GNWT) with a foundation of scientific literature to build from with the suggestion of additional phases to further explore and expand the literature available to support prescribed fire in NWT. This could include a deeper dive into the literature available on the topics above as well as hazard identification, risk assessment procedures, landscape level mitigation that incorporates fuel modification through harvesting, success/challenges in prescribed burning around northern communities, climate change interactions with prescribed fire, fire behaviour and fire effects in norther latitudes, previous research conducted in northern latitudes circumpolar/circumboreal (i.e. research results from NWT sites and other locations), traditional and cultural interactions with fire, and other topics.

In Phase 2 of this project, SMC recommends an additional review specific to the area around Fort Good Hope is warranted especially with respect to changing climate. This could be conducted with a search on: potential prescriptions, additional information on the ecological site descriptions in the area, and climate adapted species to be promoted such as species that are going to be well suited for the climate expected in 50 years. A small investigation was done into what the climate is project to be in the next 50 years and what species will be present, however, this warrants further time and resources to flesh out. Additional exploration includes the change in fire behaviour and potential transition from conifer to deciduous such including the work by Carlson and ALCES (www.alces.ca), other current research in the area by J. Johnson, M. Flannigan and B. Sieben (climate modeling). A brief introduction to B. Sieben's work was added during the revisions of Phase 1.

Citation: *Leverkus, S.E.R. and J.D. Scasta. 2018. Scientific Literature Review: Phase 1. Shifting Mosaics Consulting, Fort Nelson, British Columbia, Canada in partial fulfillment of contract # SC456069 for the Government of the Northwest Territories, Fort Smith, Northwest Territories, Canada.*

INTRODUCTION AND METHODOLOGY

We conducted a high-level review of scientific literature using academic literature search engines (specifically, Thomson Reuters Web of Science and Google Scholar) for fire search terms including northern Canada fire, boreal fire regime, historical fire regimes of the boreal, prescribed fire in Canada, wildlife search terms, and author search terms (i.e. Flannigan, Wotton, Parminter, Hawkes, Turetsky, Amiro, Stocks, Martell, Beck, Bergeron, Van Wagner, Alexander, Johnson, DeLong). All literature current to November 2015 was reviewed (Leverkus 2015) with additional review from 2014 to present where the first 100 search results were screened for relevance and inclusion in this literature review. It was common to find papers by specific authors although the author of interest was frequently not the first author (for example – for Mike Flannigan is a co-author on Parisien *et al*. 2014 and Wang *et al*. 2015). The realization of the breadth and depth of this literature review was possible because of the PhD research and thesis by Dr. Sonja Leverkus and her committee of Dr. Samuel Fuhlendorf, Dr. Marten Geertsema, Dr. David Engle, Dr. Dwayne Elmore, and Dr. Kristen Baum with integral support by Dr. J. Derek Scasta.

RESULTS

Fire in the Boreal

The circumboreal forest is the most extensive, intact, terrestrial biome on earth and is estimated to contain more than 100,000 species of flora and fauna (Zasada et al. 1997; Schmiegelow et al. 2006; Burton et al. 2008, Flannigan et al. 2009). Lightning and human-caused (anthropogenic) ignitions have resulted in a patchwork mosaic across the boreal forest since the last Ice Age (Rowe and Scotter 1973, Goldammer and Furyaev 1996, Stocks et al. 2003). Evidence of past fires are captured through fire statistics (Johnson 1992), charcoal in soil profiles (Rowe and Scotter 1973, Larsen and MacDonald 1998), morphological characteristics and age structure of vegetation species (Rowe and Scotter 1973), oral accounts by Indigenous Communities (Lewis and Ferguson 1988, Johnson 1992, Suffling and Speller 1998).

Over a broad temporal scale of the last millennium, climatic conditions have changed with noteworthy warming in the Medieval Warm Period, and subsequent cooling during the Little Ice Age (Grove 2001). Low lying portions of the boreal forest have experienced paludification which favours the initiation of muskeg formation some 6,000 years ago (MacDonald and McLeod 1996). Determining a fire return interval for a particular area proves challenging in light of the variability of climate and complex synergies between various disturbance agents such as forest fire, geomorphological events, windstorms, insect outbreaks and floods (Delong et al. 2013). In the boreal, the fire return interval ranges from small frequent burns (burning of yards and corridors as documented by Lewis and Ferguson 1988) to larger wildfire events with century-scale return periods (Heinselman 1981, Lewis and Ferguson 1988, Kasischke et al. 1995, Larsen and MacDonald 1998).

Since the boreal forest is a landscape with a short, but intense growing season where natural disturbances are active (Bergeron et al. 2004, Burton et al. 2006), numerous fire-adaptations of species occur including: the ability to resprout after fire (Aspen (*Populus tremuloides Michx*) (Schier and Campbell 1978)), seed-banking (Bicknell's geranium (*Geranium bicknellii*) and Corydalis species (*Corydalis sempervirens (L.) Pers., C. aurea* Willd.) (MacKinnon et al. 1999, Catling et al. 2001)), and serotinous cones (Lodgepole pine (*Pinus contorta var. latifolia Douglas ex Louden*) (MacKinnon et al. 1999)). As a critical ecosystem driver across varying spatio-temporal scales in the boreal forest, fire influences plant species composition and structure, regulates diseases and insects, maintains and promotes the productivity and diversity of vegetation types, and affects nutrient cycling and energy fluxes (Rowe and Scotter 1973, Volney and Hirsch 1996).

Fire in the NWT

The Northwest Territories (NWT) of Canada have a history of fire activity that has potentially been escalating the last decade or so according to the Canadian Wildland Fire Information System and Canadian National Fire Database (see figure below). As such, the consideration of how to apply prescribed fire in a safe and effective approach is of interest to stakeholders in the Territories. In the 2014 NWT fire season report (http://www.enr.gov.nt.ca/sites/enr/files/web_pdf_fmd_2014_fire_season_review_report_4_may_2015.pdf), some communities inquired about the use of prescribed fire around communities to remove fuel (prescribed fire is also mentioned 2 other times; p. 6 – Introduction, 2nd paragraph; and in the Executive Summary). Dr. Higueara with the Alaska Fire Science Exchange has an excellent powerpoint about fire in the far north (https://www.frames.gov/files/1413/4937/9220/2012_05_24_AFSC_Higuera.pdf).

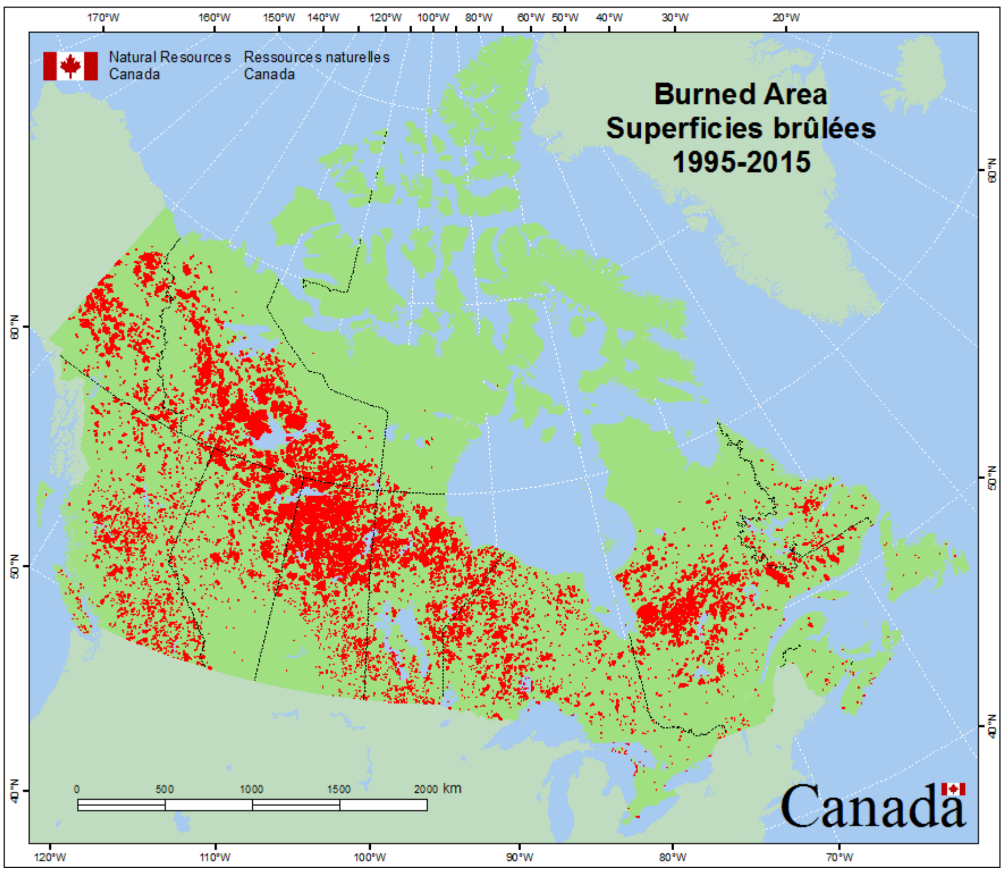

Figure from the Canadian Wildland Fire Information System, Canadian National Fire Database (http://cwfis.cfs.nrcan.gc.ca/ha/nfdb?type=hands&year=9999).

Utility of prescribed fire

Fire, in a controlled and managed setting, can be a landscape management tool that is also an ecological process with many important applications and effects. Prescribed fire is the application of fire to the land using a prescription which outlines objectives, treatment methods and monitoring. We provide a brief summary of prescribed fire in the following discussion.

Prescribed fire can **reduce fuel loads and continuity** and its effects on fuels can reduce the size, intensity, and damage of wildfires (Fernandes and Botehlo 2003). Prescribed fire can also **remove logging debris and prepare sites for planting** (Weir 2009; Renard et al. 2016). Prescribed fire can be used to **manage vegetation succession** including the maintenance of open areas or for a specific forest type (Carleton and Maclellan 1994; Weber and Stocks 1998). Prescribed fire, and fires in general, can also **mitigate insect and disease outbreaks** for plants (such as bark beetles in some cases), animals (including both internal and external parasites), and humans (including certain annoying insects) (McCullough et al. 1998; Scasta 2015). Prescribed fire can **enhance herbaceous forage** crude protein, palatability, nutrient density, and biomass production which can be important for livestock and certain wildlife species (Scasta et al. 2016). Fire can **establish diverse habitat** features that are important for a suite of wildlife species at different seasonal or life stages for broad guilds of invertebrates, birds, reptiles, amphibians, small mammals, large mammals, and apex predators (Scasta et al. 2016). Prescribed fire has other functions such as improving access, nutrient cycling, and managing habitat for species at risk or fire dependent species.

The human dimension of fire has been a historical component of the boreal ecosystem (Seip and Bunnell 1985, Peck and Peek 1991, Sittler 2013, Leverkus 2015). As an example, Leverkus (2015) conducted an analysis of prescribed fire in northeast British Columbia. Results showed that prescribed fire predominantly occurs on south facing slopes where 117 195 ha of seven watersheds have burned compared to 21 255 ha on north facing slopes of the same watersheds. This is due to past prescribed fires targeting south facing slopes on the north sides of rivers to enhance resources for ungulates (Peck and Peek 1991). It is suggested that prescribed fire needs to continue to be used in the region to promote, maintain and enhance the boreal ecosystem for ungulates (Seip and Bunnell 1985, Peck and Peek 1991, Sittler 2013, Leverkus 2015). In locations where prescribed fire is recently being considered, there are significant opportunities to engage in strategic planning processes which include implementation and continuation through space and time (Note: Peace-Liard Prescribed Fire Program and Yukon Fire Risk Assessment).

Burning near communities

From a community protection perspective, it is the fires that burn in the wildland urban interface (WUI) that are part of increasing suppression costs. It is often a few very large fires in the WUI that cause the most property loss and suppression cost and according to the Canada Wildland Fire Strategy "*Provincial wildland fire management agencies cannot deal effectively with interface issues on their own.*" (Hirsch and Fuglem 2006). Willingness-to-pay (WTP) values for prescribed fire in Colorado USA indicate that residents are aware that wildfire is a risk and are open minded about the use of prescribed fire as a mitigation tool. Respondents indicated willingness to pay a tax for burning on the surrounding public lands which could reduce the financial burden for the general public (Kaval et al. 2006). Under the US National Fire Plan (NFP) from (2004–2008), a total of 44,000 fuel treatments were applied in the west United States; yet only 11% of the area treated was within the WUI (3% of the area treated within the WUI plus 8% was in the 2.5-km buffer around the WUI) suggesting that more applications in the WUI rather than extremely remote areas are needed to reduce the fire risk to communities (Schoennagel 2009). Communities that have experienced wildfires and that have citizens demonstrating a deep attachment to place may be the most amenable to incorporating fire risk mitigation tactics (Bihari and Ryan 2009).

In order to get started it might be prudent to consider how prescribed fire cooperatives/associations have started in other regions of North America (Weir et al. 2015). This cooperative and collaborative approach helps to overcome many of the barriers to starting a safe and effective prescribed burning program such as lack of expertise, lack of equipment, fear of liability, etc. Details about fire escapes, injuries, lawsuits/insurance claims, etc. for prescribed fire associations are summarized in Weir et al. (2016). This approach has been described as empowering and equipping for stakeholders (Taylor 2005). In addition, prescribed burning training exchanges (TREX) are a new approach to enhancing learning and expertise in the subject of prescribed fire and offer a model for facilitating this process in a new prescribed fire program (http://swfireconsortium.org/wp-content/uploads/2013/12/Bailey_webinar_RxFire_Trainings.pdf). Additional suggestions could arise from the recently developed and evolved Peace-Liard Prescribed Fire Program and the strategic engagement processes in its development as well as from the FireSmart program (i.e. Home Ignition Zone Assessment pilot project in Fort Nelson, BC) and debriefs from Slave Lake and Fort MacMurray wildfires.

Fire and permafrost

Burn (1998) conducted a study assessing soil profile temperatures and permafrost responses relative to a wildfire in 1958 by using paired burned/unburned areas in the Takhini River Valle in the southern Yukon Territory. The authors found that there had been little recovery of the forest vegetation since the fire (sampling approximately 40 years post-burn) and that there was detectable permafrost degradation. Specifically, the permafrost was thawing from top and bottom and the depth below the ground surface to thermafrost had increased as had mean annual temperature. Modeling suggests that more than a millennia would be required for permanent degradation of the permafrost here and suggest that the permafrost is relatively persistent. Differences in ground temperature were most noticeable during the summer (see Figure 11 below from the study) and the authors suggest that as vegetation succession continues permafrost degradation will be inhibited.

Fig. 11. Six-year time series, beginning in January 1991, of 1.5 m ground temperatures at forested (□) and burned (▲) sites, Takhini River valley. The 6-year mean temperatures at this depth are –0.8°C and 0.1°C for the forest and burned sites, respectively.

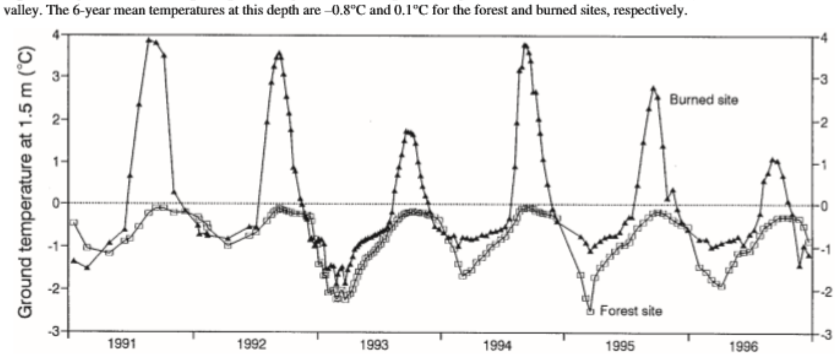

Figure from Burn 1998 demonstrating soil temperatures in burned and unburned sites.

Soil temperatures of permafrost under current and future climate forecasts are regulated by a complex interaction of vegetation cover, soil properties, surface wetness, and snow cover. Loranty et al. (2016) conducted a 30-year spatial analysis of the circum-arctic permafrost zone which is the northern hemisphere north of 60° N latitude. During this timeframe, increases of 23% and 41% for greening and 5% and 12% for browning were noted for the continuous and discontinuous permafrost zones. Shrub expansion is associated with the greening trend at the landscape scale and may insulate soil temperatures or shrub expansion may alter albedo feedbacks at the regional scale and lead to permafrost thaw; thus how shrub expansion will affect permafrost soil carbon dynamics is still undetermined. Fire was also shown to affect a much smaller proportion of the total area than vegetation productivity changes and thus affects a smaller amount of permafrost soil carbon (see Figures 3 and 4 below and not the different y-scale ranges (0-70 C_P (Pg)) for productivity trend C_P pool versus 0-4 CP (Pg)) for burned area CP pool).

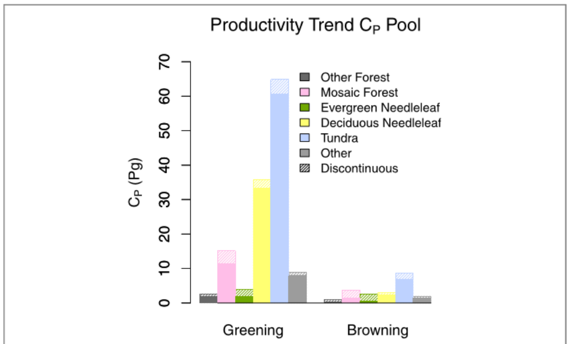

Figure 3. Soil carbon pools (0–1 m) for areas of each vegetation class that exhibit greening (left) and browning (right) trends from 1982 to 2012. Solid portions of the bars represent areas of continuous permafrost and hashed portions represent areas of discontinuous permafrost.

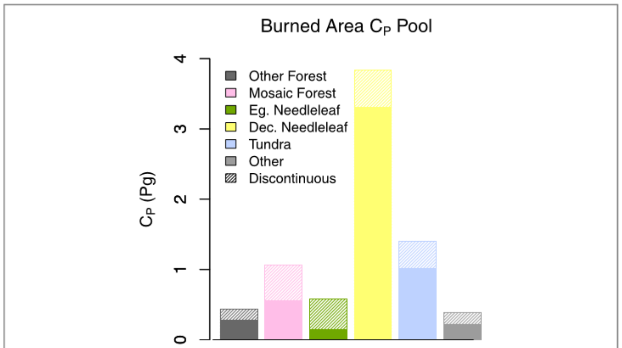

Figure 4. Soil carbon pools (0–1 m) in areas that burned during the 2000–2014 period, by vegetation class. Solid portions of the bars represent areas of continuous permafrost and hashed portions represent areas of discontinuous permafrost.

Figure from Loranty et al. 2016 showing productivity trends and burned area trends relative to the circum-artic thermafrost carbon pools.

Further investigation into permafrost interactions with fire (prescribed and wild) could prove useful for decision makers in the NWT. We suggest that prescribed fire could have less of an impact on permafrost just by the nature that the prescription can be implemented under desirable and planned conditions to achieve objectives and that there might be ways to prevent permafrost degradation depending on season of burn, depth of consumption, and targeted aboveground species.

Climate change in northern latitudes

Young et al. (2017) modeled the 30-yr probability of fire occurrence as a function of climate and landscape features for Alaskan boreal and tundra. Summer temperature and annual moisture availability have historically controlled the fire regimes with specific fire probability thresholds for temperatures above the average July temperature of 13.4 °C and below an annual moisture availability (i.e. P-PET) of approximately 150 mm. Using the RCP 6.0 change scenario, the authors conclude "*Regions with historically low flammability, including tundra and the forest–tundra boundary, are particularly vulnerable to climatically induced changes in fire activity, with up to a fourfold increase in the 30-yr probability of fire occurrence by 2100.*" and that novel fire regimes are to be expected.

Fire forecasts predict that the area burned in the North American boreal will increase by 30% to 500% by the end of the 21st century (Héon et al. 2014), and that a 35% to 400% increase in fire spread days in Canada by 2050 is to be expected. These forecasts will result in a boreal burn rate change from 1.4% of the land area per year from 1810 to 1909 to 2.4% from 1910 to 2013 (Héon et al. 2014). For regions with permafrost (i.e., arctic and sub-arctic), climate induced carbon feedbacks due to permafrost melting and a warming climate include accelerated microbial breakdown of carbon and increased release of carbon dioxide and methane. The evidence available today suggests a "*gradual and prolonged release of greenhouse gas emissions in a warming climate*" for these regions (Schuur et al. 2015). Forkel et al. (2016) reported a similar trend for enhanced carbon dioxide exchange seasonally due to the plant production amplification occurring in northern ecosystems. Northern latitudes will also be highly susceptible to biological invasions as the climate warms (Pauchard et al. 2016).

Climate modelling specific to NWT – personal communication with B. Sieben, May 13 2018

B. Sieben reports that they have been collaborating with the University of Alaska Fairbanks (UAF) to generate the latest 5th assessment climate projections for the NWT found at the following website: https://www.snap.uaf.edu/sites/all/modules/snap_community_charts/charts.php#baseline=cru32&community=1242&dataset=1&scenario=rcp85&units=metric&variability=0. If you type Northwest Territories in the box you can see all the communities available. On this site you can change temperature to precipitation and select the Representation Concentration Pathway (Emission Scenarios). RCP 8.5 is our current trajectory. If you turn on inter-model variability you can get an idea of the range (bars will appear showing you the range of five models).

B. Sieben also provided links to precip and temp for NWT as a GEOTIFF using the latest AR5 projections. B. Sieben recommends using the 5 model average. The 5 model average exists up to the end of the century found at: http://ckan.snap.uaf.edu/dataset/projected-monthly-precipitation-products-10-min-cmip5-ar5
http://ckan.snap.uaf.edu/dataset/projected-monthly-temperature-products-10-min-cmip5-ar5

It is strongly recommended to further engage with B. Sieben as he will be able to continue providing expert recommendations, guidance, advice, and science.

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Ignition prescriptions for boreal and tundra

Hinzman et al. (2003) conducted a watershed scale (970 ha) prescribed fire in Alaska and they suggest it is the most studied fire in boreal forest and discontinuous permafrost (i.e., FROSTFIRE). One third of the watershed was black spruce and the remainder was birch-aspen deciduous forest on south facing slopes and wet *Sphagnum* peat moss communities along streams. A burn plan has been publicly available but we could not locate at this time (there is a broken hyperlink here https://www.fs.fed.us/pnw/fera/research/targeted/frostfire/documents/ea.shtml). A burn prescription is presented in the paper and has been inserted into this report in the following pages.

Table 1. Frostfire Burn Prescription With Acceptable Parameter Range	Low	High	Desired
Temperature (°C)	17	27	21
Relative Humidity (%)	40	25	30
Live Fuel Moisture (% Spruce Needles)	125	70	85
10 m Wind Speed (kph)	5	12	8
Wind Direction	Southwest	East	Southeast
Slope (%)	0–32	0–23	0–32
FFMC[a]	88.5	92	91
DMC[b]	59	71	63
DC[c]	300	475	350
BUI[d]	77	104	87
ISI[e]	4.4	15.2	10
FWI[f]	14	42	29

The Go/No Go prescription parameters are indicated in bold; they define a proceed versus stop prescription window. The other prescription parameters serve as guides indicating when the unit is coming into prescription and indicators for meeting scientific objectives of the prescribed burn.

[a]FFMC: Fine Fuels Moisture Content, a numerical rating of moisture content of litter and other cured fine fuels in a forest stand.

[b]DMC: Duff Moisture Code, represents moisture content of loosely compacted organic (duff) layers of moderate depth.

[c]DC: Drought Code, represents moisture content of deep compact organic layers.

[d]BUI: Buildup Index, a combination of DMC and DC that represents the total amount of fuel available to the spreading fire.

[e]ISI: Initial Spread Index, a combination of wind speed and FFMC, representing fire spread rate without the influence of variable fuel quantity.

[f]FWI: Fire Weather Index, a combination of ISI and BUI that represents the intensity of a spreading fire as energy output rate per unit length of fire front, loosely defined as an estimation of potential fire danger and fire behavior in an area adjacent to a weather station where weather is recorded.

Table from Hinzman et al. 2003 with fire prescriptions for the FROSTFIRE research project.

It is important to note that unprecedented precautions were taken including a 5cm fire hose that went around the entire perimeter of the fire, pumps installed in the watershed stream, large water tanks pre-positioned around the fire, 100+ firefighters were on the site the day of the burn, and 1 fixed wing and 2 helicopters were on site the day of the burn. Aerial and hand ignition were used. One escape occurred and burned ~2.8 ha. The black spruce portion burned well but the birch-aspen deciduous forest and Sphagnum moss did not burn well.

A strategy for altering fire spread (as indicated in the Hinzman et al. (2003) study above), is the integration of less flammable deciduous broadleaf vegetation into the conifer dominated boreal landscape (Girardin et al. 2013). Regarding flammability, "*Broadleaf deciduous stands are characterized by higher leaf moisture loading and lower flammability and rate of wildfire ignition and initiation than needleleaf evergreen stands*" and the increase of these species in the boreal landscape could be an offsetting measure for climate change induced fire regime changes. Based on an evaluation of charcoal deposition, the following two models of deciduous versus conifer vegetation and fire occurrence proposed by Girardin et al. (2013) conclude "*we estimate that its (*i.e., deciduous vegetation flammability added for context*) feedback may be large enough to offset the projected climate change impacts on drought conditions*.". The two relevant models from Girardin et al. (2013) are below:

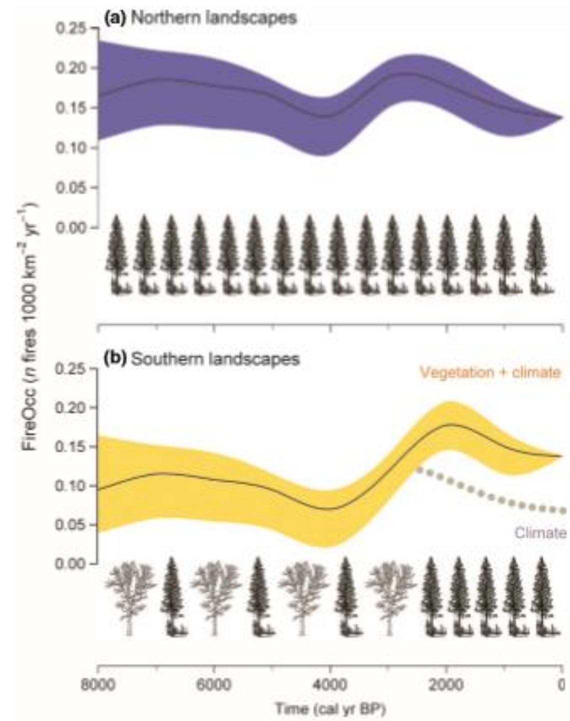

Fig. 4 Projected changes in the occurrence of large wildfires (FireOcc) in (a) northern and (b) southern landscapes from 8000 to 0 BP (calibrated years before present) simulated using climatic data from the HadCM3 general circulation model (GCM) and vegetation changes deduced from pollen analyses (see Fig. 3d–e). The shaded area is the 90% CI. In (a), a fixed vegetation composition dominated by needleleaf forests was set throughout the entire period. In (b), vegetation was manipulated (*Vegetation + climate*) with a shift from a boreal mixedwood to a needleleaf-dominated forest at 2000 BP. The status quo scenario of no vegetation change (*Climate*) is also shown in (b).

Figure from Girardin et al. 2013 showing fire occurrence in the far north relative to conifer and deciduous forest vegetation changes.

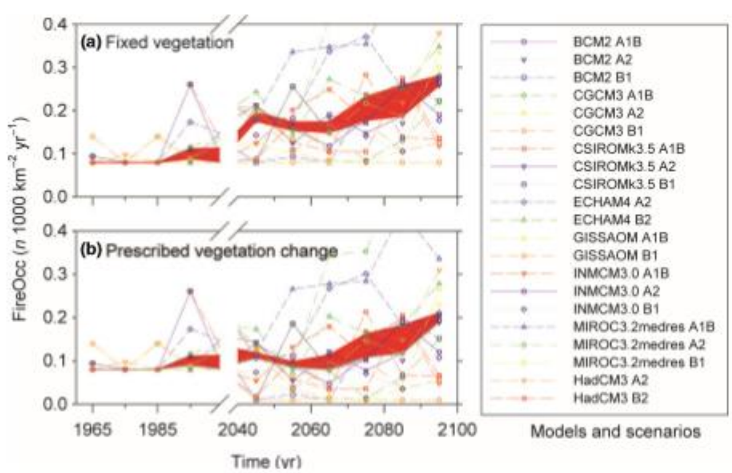

Fig. 5 Projected changes in the occurrence of large wildfires (FireOcc) in the modern northern needleleaf landscape over the 21st Century simulated from an ensemble of eight global climate models forced by various scenarios for greenhouse gas emissions. A 90% bootstrap confidence interval (CI) for the ensemble median is shown (red shading). In scenario (a), vegetation was set with a fixed needleleaf forest throughout all periods. In scenario (b), vegetation was manipulated with a shift from a needleleaf to a boreal mixedwood forest at AD 2040. In scenario (a), mean FireOcc calculated over the interval 2041–2100 is significantly greater than mean FireOcc calculated over the interval 1961–1999 (one-sided Student's *t*-test $P < 0.05$). In scenario (b), 2041–2100 FireOcc is not significantly greater than 1961–1999 FireOcc.

Figure from Girardin et al. 2013 showing projected fire occurrence.

Developing prescribed fire prescriptions and projects to better understand associated vegetation changes relative to fire severity and deciduous vegetation have been conducted in Alaska (Paragi2003). Additional details about these Alaskan fires and prescriptions are available in Paragi and Haggstrom (2015), and specifically, from a 1998 prescribed burn that increased shrub and deciduous sapling cover from 15% to 53% after 4 growing seasons in the 25 km^2 study. There has also been recent developments in the use of remote sensing to document burn severity relative to vegetation types using dNBR (differenced Normalized Burn Ratios) that could have a high level of utility in managing vegetation succession and change relative to fire in boreal and tundra systems (Allen and Sorbel 2008).

Fire research in the NWT

The Northwest Territories (NWT) have a strong history of fire research. For example, the International Crown Fire Modeling Experiment (ICFME), located between Fort Providence and Yellowknife, NWT was an international effort between Canada, United States, and Russia to empirically assess crown fire behavior in a controlled experiment. It is now called the Canadian Boreal Community FireSmart Research Site. Plots were established with 50 m fire breaks and ignited with a flame thrower. This project has generated a lot of cutting edge fire research (List of publications available here: https://www.frames.gov/partner-sites/applied-fire-behavior/international-crown-fire-modeling-experiment-icfme/; http://wildfire.fpinnovations.ca/Research/NWTProject.asp; https://www.frames.gov/catalog/7881).

Cruz et al. (2005) developed and tested models for crown fire rate of spread in boreal conifer forests using the ICFME experimental data and reported that active crown fire rate of spread can be predicted by 10-m open wind speed, fine fuel moisture, and canopy bulk density. Forest, fuel, weather, and behavioral characteristics of this data set are provided below in Table 1 from this study below.

Table 1. Basic descriptive statistics associated with the data set used in the development and evaluation of the crown fire rate of spread models.

	Active crown fires (n = 24)				Passive crown fires (n = 13)			
Variable	Min.	Max.	Mean	Std. dev.	Min.	Max.	Mean	Std. dev.
Stand basal area ($m^2 \cdot ha^{-1}$)	3.35	50	26.8	16.3	4.14	35.2	18.4	10.4
Stand density (trees$\cdot ha^{-1}$)	887	6750	3561	1454	597	9276	3656	3481
Stand height (m)	2.9	14	7.9	3.8	4.1	19	11.7	6.6
Crown ratio (fraction)	0.5	0.88	0.78	0.12	0.37	0.9	0.74	0.15
Canopy base height (m)	0.4	7	2.1	2	0.8	12	3	3.2
Canopy bulk density ($kg \cdot m^{-3}$)	0.12	0.48	0.27	0.09	0.05	0.37	0.16	0.1
10-m open wind speed ($km \cdot h^{-1}$)	5	32.1	15.8	6.7	5	29	16.3	6.3
Estimated fine fuel moisture content (%)	7	12	8.8	1.3	7	11	8.6	1.2
Surface fuel consumption ($kg \cdot m^{-2}$)	0.66	2.4	1.6	0.5	0.9	3.2	1.7	0.7
Foliar moisture content (%)	78	135	107	11.5	75	118	102	15.4
Rate of fire spread ($m \cdot min^{-1}$)	7.5	51.4	22.6	12.6	3.35	15.4	7.1	4
Fireline intensity ($kW \cdot m^{-1}$)	4230	45 200	16 918	10 746	1698	17 000	5127	4239

Note: The 24 experimental active crown fires used in the present study included the following: fires 2, 3, 4, 5, 6, 11a, 11b, 12, 13, and 14 in Stocks (1987*a*); fire 3/91 in Stocks and Hartley (1995); fires L2, L5, and L5A in Alexander et al. (1991); fires C4, C6, and R1 in Van Wagner (1968, 1977); "water" treatment fire in Newstead and Alexander (1983); and the fires carried out in the Big Fish Lake experimental burning plots (Alexander and Quintilio 1990) 1, 9, 11, 12, 17, and 21 (M.E. Alexander, unpublished data). The 13 experimental passive crown fires used in the present study included the following: fire 17 in Stocks (1987*a*); fires 5, 9, and 12 in Stocks (1989); fires 4b and 6 in Quintilio et al. (1977); fires L1, L3, and L4 in Alexander et al. (1991); the "tenogum" treatment fire in Newstead and Alexander (1983); the Steen River experimental fire (Kiil 1975); fires 5 and 7 in Weber et al. (1987). Note that fire 7 in Weber et al. (1987) is referred to as fire SC in Van Wagner (1977).

Table from Cruz et al. 2005 assessment of crown fire rate spread models.

Burning meadows

There has been some research on using prescribed fire in meadows. Quinlan et al. (2003) assessed the vegetation responses of wet meadows to spring fires in 1992, 1993, and 1995 in the Hook Lake Bison Range. Spring burns appeared to alter willow vigor, but willow survival was high even on the most frequently burned areas (~76%). In addition, frequent spring burning seemed to select for *Carex aenea* and *Juncus balticus*. There is a significant body of literature discussing the burning of meadows that can be further explored if requested.

Wildlife interactions with fire

The ecological process of fire as it is spatially and temporally distributed across landscapes of varying scale is important for wildlife and its habitat. The shifting mosaic that results from the spatio-temporal distribution of fire results in heterogeneity which has been argued successfully as the root of biological diversity and the basis for conservation (Fuhlendorf *et al.* 2006). When we consider important species across the NWT, there must be a recognition that their habitat needs and the required resources for each species requires varying degrees of time since disturbance, or specifically time since fire (Leverkus *et al.* 2017). The importance of this fire-driven habitat heterogeneity spans trophic levels as it can be important for broad guilds of invertebrates, birds, reptiles, amphibians, small mammals, large mammals, and apex predators (Scasta *et al*. 2016).

Wildlife have different resource requirements for varying time since fire to meet their habitat needs. Left to right: Wood bison (S. Leverkus), grouse (S. Leverkus), fisher (C.M. Gitscheff), caribou (S. Leverkus).

We highlight several species including their habitat requirements and how that interacts with fire in the following discussion, however, there is significant space for a deeper dive into each species and into the topic of habitat and wildlife interactions with fire. Per Leverkus (2015), Leverkus et al. (2017), Leverkus et al*.* (2018) varied time since fire influences species distribution and resource selection including:

- access to and abundance of browse, forage, insect, fruit and berries (Seip and Bunnell 1984, Seip and Bunnell and 1985, Munro et al. 2006, Ciarniello et al. 2007, Stevens et al. 2007)
- availability and abundance of prey species and their habitat requirements (Boutin et al. 2003, Sullivan et al. 2006, Hatler and Beal 2010)
- hunting areas and riparian areas (Krebs et al. 1995, Hatler and Beal 2010)
- host plants and vegetation important for invertebrate lifecycles (Baum and Sharber 2012)
- vertical structure such as coarse woody debris, snags, rotting trees and layered overhead vegetation for shelter, denning, protection, roosting, cover, escape, breeding, lambing, calving, naissance and migrating staging areas (Seip and Bunnell 1984, Hobson and Schieck 1999, Schieck and Hobson 2000, Fisher and Wilkinson 2005, Hatler and Beal 2010)

- seasonal movements influenced by snow depth, exposure to sun and wind, travel corridors (Hatler and Beal 2010)
- habitat connectivity and suitability (Holsinger and Keane 2011)
- ecological processes (Dublin 1990) and refugia (Elliott 1983)

Birds

Bird species have a variety of structural requirements and bird species which may be present include: Upland sandpiper (*Bartramia longicauda*) and Nelson's sharp-tailed sparrow (*Ammodramus nelson*). Sandercock et al. (2015) and Hovick et al. (2017) have recently published research documenting the interaction between prescribed fire on resource selection and habitat for sandpipers and shorebirds, respectively. Recent time since fire is important to a broad range of birds inhabiting the boreal (Nappi et al. 2004).

Bison

Bison, a megafauna species, have empirically been shown to be attracted to recently burned areas. Specifically, wood bison (*Bison bison athabascae*) select for early-seral grasslands or limited time since fire (Leverkus 2015). Prior to 1800, more than several hundred thousand wood bison are reported to have roamed across Alberta, BC, the NWT, and the Yukon (Soper 1941, MacGregor 1952, Harper et al. 2000, Stephenson et al. 2001). Wood bison are considered the largest species of megafauna in these landscapes (Gates and Larter 1990, Larter and Gates 1990, Campbell et al. 1994, Harper 2002, Jensen 2005).

The diet of bison primarily consists of sedges and grasses with a minor component of terrestrial lichen available in grassy meadows and shrubby savannas (Harper 2002). Bison require open rangelands and sedge meadows for foraging and wallowing (Soper 1941, Larter and Gates 1990, Harper and Gates 2000, Harper et al. 2000, Fortin et al. 2002, Leverkus et al. 2017), open forest for rutting, rubbing and foraging (Soper 1941, Larter and Gates 1990, Harper et al. 2000, Fortin et al. 2002, Leverkus et al. 2017), dense forest for cover, rubbing and foraging (Soper 1941, Larter and Gates 1990), and riparian areas for foraging and wallowing (Soper 1941, DeLong et al. 1991, Larter and Gates 1990, Harper et al. 2000, Fortin et al. 2002)(note diagram in appendix). Bison have an effective digestive system with ability to forage in areas of recent disturbance and ability to move and use a variety of cover types (Stephenson et al. 2001), while also being adapted to low temperatures and snow conditions (Stephenson et al. 2001). Others have also suggested that wood bison historically foraged for grasses amid forests of black and white spruce (*Picea mariana* and *P. glauca*), aspen (*Populus tremuloides*), jack and lodgepole pine (*Pinus banksiana* and *P. contorta var. latifolia*), and poplar (*Populus balsamifera*), and that they exploited large areas of open land (Yerbury 1980).

Results by Leverkus (2015) show that wood bison are strongly attracted to linear development and that they select for open areas and avoided forests. Leverkus (2015) suggests that there is a need for more open areas available for bison selection which can be achieved through the application of prescribed fire to increase openness and to promote pyric herbivory which could assist in drawing bison away from hazardous areas (Fuhlendorf et al. 2009). Since the diet of bison primarily consists of sedges and grasses with a minor component of terrestrial lichen available in grassy meadows and shrubby savannas (Harper 2002), processes which produce such vegetation are important for bison. Time since disturbance and number of disturbances drive the availability, access to and quality of grazing areas for bison in the Boreal.

Moose

While moose (*Alces alces*) responses to fire can vary there are many studies demonstrating an attraction to relatively recently burned areas for enhanced foraging and browsing. The tradeoff appears to be a balance between exposure to large carnivores in open burned areas and the shrub and forage regeneration that occurs as time since fire elapses (see the figure below adapted from Franzman and Schwartz 1997). Fisher et al. (2005) report that moose abundance increases from 0 to 25 years after fire or timber harvest, while caribou abundance is lower due to reduced lichen availability (especially after burns) and that caribou use is highest in areas with 26 to >125 years since fire compared to a moose decrease in use in these areas.

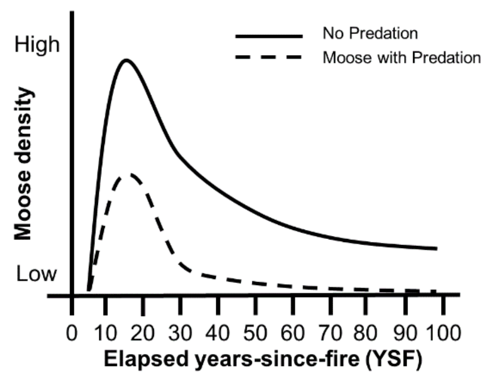

Figure showing moose response to fire relative to predation (adapted from Franzman and Schwartz (1997).

A study of moose responses to a 3,000 acre wildfire in Alaska indicate that moose foraged in the burn area within a few months after the fire, especially that following winter, with primary attractant appearing to be willows. A study of a 14,000 acre wildfire in Minnesota reported a moose density increase of 4 times (from 0.5 moose per square mile to 2.0 moose per square mile) in the burned area within 2 years of the fire although the authors had a hard time separating the attraction to the burned area from an immigration event.

Gasaway et al. (1989) report variable responses up to 5 years after a 500 km^2 burn in Alaska and conclude that "Use of recently burned areas by moose varies widely, and hence, conclusions should be extrapolated cautiously. Use is likely related to intensity of fire, regrowth of moose browse, adjacent habitat, and pre-fire moose density and movement patterns". These authors conclude that their results were likely variable because moose density was low in this area and because moose do not randomly search for better habitat.

Caribou

Caribou (*Rangifer sp.*) have a very complex ecological interaction with fire due to the high abundance on lichens. For example, caribou abundance is lower due to reduced lichen availability (especially after burns) and caribou use is highest in areas with 26 to >125 years since fire compared to a moose decrease in use in these types of areas (Fisher et al. 2005). Joly et al. (2007) reported that Alaskan caribou strongly selected against burned areas within the tundra ecosystem, with a particular avoidance of 26 to 55 year old burns and the interior portions of burned areas. Klein (1982) presents an overview of fire, lichens, and caribou and classifies short-term and long-term effects for this interaction as 0 to 70 years and > 70 years respectively, thus, thinking about the fire*lichen*caribou interaction requires a consideration of decadal and century processes.

Generally, while barren-ground caribou avoided areas with a high density of burns, they have been documented to use early-seral habitat considerably and areas adjacent to burn area boundaries with the conclusion that at some spatial and temporal scales, some individual barren-ground caribou may be less averse to fire than previously thought (Anderson and Johnson 2014). Recent caribou papers include Anderson and Johnson 2014; Beguin et al. 2015; Bichet et al. 2016; Gustine et al. 2014; Mallon et al. 2016; Polfus et al. 2014; Rickbeil et al. 2016; Whitman et al. 2017. Anderson and Johnson (2014) report on barren-ground caribou response to fire from the Northwest Territories of Canada. Generally, while barren-ground caribou avoided areas with a high density of burns, they did use early-seral habitat considerably and areas adjacent to burn area boundaries. The authors concluded that at some spatial and temporal scales, some individual barren-ground caribou may be less averse to fire than previously thought (Anderson and Johnson 2014).

Rickbeil et al. (2016) assessed caribou in the Northwest Territories and their response to fire and concluded that the effect of fire on caribou distribution is more of a function of forest stand structure than lichen availability. For further discussion regarding the interaction between caribou and fire, we suggest a review of McLoughlin et al. 2016 (pp 12-13, 37 – 39) and Saperstein and Joly 2004. We highlight new research from Dr. P. McLoughlin's lab at the University of Saskatchewan which provides important insight to the interaction of caribou with fire.

Fur-bearers

Fur-bearers are an important feature on the landscape of the NWT. Furbearing animals require varying vegetation structure across their home ranges. Natcher (2004) reports that fires created browse that was important for increasing prey species of furbearing predators, such as rabbits and voles. It is important to recognize the habitat requirements not only of furbearing species across the landscape, but also the prey that they feed on and what their habitat requirements consist of (Hatler and Beal 2010). If habitat needs are lacking, furbearer populations are unable to perform and grow to their fullest capacity (Hatler and Beal 2010). For example, fisher (*Pekania pennanti*) are a forest-dwelling species which select to den in trees that have a fire scar or wound and they hunt for prey in habitats with less vertical structure that are more open indicating an interaction with disturbance processes resulting in heterogeneity (Hatler and Beal 2010, Leverkus et al. 2017). Snowshoe hares (*Lepus americanus*) are a primary food source for fisher and areas with time since fire of 15 to 40 years are highly suitable and capable for hares as well as for hunting areas for fisher (Boutin et al. 2003, Sullivan et al. 2006, Hatler and Beal 2010). Food and predation are known to be critical interactions in the life cycle of hares which in turn influence the distribution of fisher and other species such as lynx (Krebs et al. 1995). Lynx typically forage in younger aged forests, however they also select older forests where there are thickly branched trees and tangles of coarse woody debris from deadfall for shelter, denning and protection (Hatler and Beal 2010).

Wolverine (*Gulo gulo*) typically select for high elevation forests and alpine tundra but they also utilize a variety of lower-elevation areas particularly in the winter (Hatler and Beal 2010) where their resource selection is closely linked with the availability and distribution of their prey including rodents, ungulates, birds, berries, and carrion (Hatler and Beal 2010). The food resources for wolverine have an interaction with time since fire in their habitat. The distribution of the gray wolf (*Canis lupus*) is affected by snow depth in the winter and selected areas where ungulates such as moose and caribou concentrate (Hatler and Beal 2010) which suggests the need for varying time since fire per the prey species habitat and resource requirements (Leverkus et al. 2017). Grizzly bears (*Ursus arctos*) are omnivores that select for multiple resources across the landscape (Munro et al. 2006) with selection being depending on vegetation availability in each area (Ciarniello et al. 2007). Such a complex spatial and temporal use of resources for habitat, food and activities of grizzly bears suggests the need for a landscape management plan that incorporates time since fire and heterogeneity resulting in variable vegetation composition, structure and distribution, as primary objectives. Black bears (*Ursus americanus*) select for burned areas and other openings on the landscape (Fisher and Wilkinson 2005).

DISCUSSION

Scientific consensus indicates that the carbon-rich boreal zone will receive impacts from a changing climate including extended fire seasons of increased fire occurrence and severity resulting in influences on terrestrial carbon cycling and storage (Weber and Flannigan 1997, Amiro et al. 2001, Stocks et al. 2003). Prescribed fire implementation and strategic fire planning could increase the ability of northern ecosystems to absorb fires across broad landscapes while also protecting communities with landscape level fuel breaks.

Developing and implementing a strategic prescribed fire program which incorporates historical fire trends and regimes with current and future objectives for the landscape of the NWT could be completed using the theory of the Landscape Disturbance Matrix (Leverkus et al. 2017). By increasing fire absorbency across the landscape, multiple values and goals can be both realized and achieved (Leverkus et al. 2017). Leroux and Schmiegelow (2007) suggest that the boreal may be the only region of the world that has the last opportunities for conservation planning and maintaining intact species assemblages and ecological processes while Pyne (2007) suggests that the future of fire in Canada promises more flame, not less. The Landscape Disturbance Matrix theory could be used to develop a matrix which is based on topoedaphic conditions and time since disturbance to meet objectives such as shifting mosaics and heterogeneity across landscapes while also providing community wildfire protection.

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APPENDIX

Glossary

Glossary of fire terms as per Leverkus et al. 2016.

Note the 2003 glossary of forest fire management terms produced by CIFFC located at: http://bcwildfire.ca/MediaRoom/Backgrounders/2003_Fire_Glossary.pdf

Fire

Fire (CIFFC 2003) is the simultaneous release of heat, light, and flame, generated by the combustion of flammable material. In a wider sense, any outbreak of fire. The Merriam-Webster dictionary defines fire as the phenomenon of combustion manifested in light, flame and heat. Pyne et al. (1996) define fire as a manifestation of a chemical reaction where flame, a gas phases phenomenon, is only part of the whole process. For this report, fire is presented and discussed in the context of wildland fire (i.e. wildfire or prescribed fire). In the Yukon, the Wildland Fire Management Branch (WFM) is comprised of wildland fire managers.

Note the difference between forest fire and wildfire as follows:

Forest fire (CIFFC 2003) is any wildfire or prescribed fire that is burning in forested areas, grass, or alpine/tundra vegetation. Variously defined for legal purposes (e.g., the State of California Public Resources Code: uncontrolled fire on lands covered wholly or in part by timber, brush, grass, grain, or other flammable vegetation). Types of fires are ground, surface, and crown (NFCG 2008).

Wildfire is an unplanned or unwanted wildland fire including unauthorized human-caused fires, escaped wildland fire use events, escaped prescribed fire projects, and all other wildland fires where the objective is to put the fire out (NFCG 2008). Contrasted with prescribed fire (CIFFC 2003).

Wildland fire is any non-structure fire that occurs in the wildland. Three distinct types of wildland fire have been defined and include wildfire, wildland fire use, and prescribed fire (NFCG 2008).

Firebreaks, fireguards, firelines (Weir 2009)

Firebreaks, fireguards, and firelines delineate the boundary of a fire and serve to contain a prescribed fire and to change the characteristics of fuel in, around, and/or ahead of a wildfire. This can be achieved through wetlining, blading with heavy machinery to expose soil, mowing, and back-burning or black-lining.

Fire history (Joint Fire Science Program, Johnson 1992)

Fire history provides the evidence of the past interaction between fire and climate. This includes the spatial and temporal extent of past fires.

Fire intensity and severity (Joint Fire Science Program, Morgan et al. 2001)

Fire intensity is a physical description about the behaviour of an individual fire and is correlated with flame length. Fire severity includes a combination of: degree of tree mortality, heat penetration into the soil and resulting effects on soil, degree of organic biomass consumption on and within the soil, change in ash and soil colour.

Fire management (BC Wildfire Service/ CIFFC 2003 and Martell 2015)

The activities concerned with the protection of people, property, and forest areas from wildfire and the use of prescribed burning for the attainment of forest management and other land use objectives, all conducted in a manner that considers environmental, social, and economic criteria. Note: Fire management represents both a land management philosophy and a land management activity. Fire management involves the strategic integration of such factors as knowledge of fire regimes, probable fire effects, values-at-risk, level of forest protection required, cost of fire-related activities, and prescribed fire technology. These factors are then incorporated into multiple-use planning, decision-making, and day-to-day activities to accomplish stated resource management objectives. Successful fire management depends on effective fire prevention, detection, and pre-suppression, having an adequate fire suppression capability, and consideration of fire ecology relationships. Fire management can be defined as "delivering the right amount of the right fire to the right place at the right time at the right cost" (Martell 2015).

Fire regime (Joint Fire Science Program, Morgan et al. 2001)

Fire regimes characterize the spatial and temporal patterns, including ecosystem impacts, of fire on the landscape. Fire regimes "reflect the fire environment, and influence the type and abundance of fuel, thereby affecting fire behaviour and fire effects through time" (Morgan et al. 2001). Important factors in describing and determining fire regimes include: frequency, severity, intensity, predictability, size, seasonality, spatial patterns, vegetation type and weather/climate patterns. Fire regimes are affected by terrain, slope, landscape pattern, ignition loads and management regimes.

Fire rotation period and fire cycle (Morgan et al. 2001)

Fire rotation period and fire cycle incorporate fire perimeters and are defined as the length of time necessary to burn an area equivalent to a specific study area. Fire cycle is calculated based on the distribution of ages in a time-since-fire model.

Fuel (Joint Fire Science Program, Pyne et al. 1996, Weir 2009)

Fuel is the vegetative material that burns in a fire. There are many characteristics to consider with fuel such as fuel quantity, continuity, size and shape, compactness, arrangement and moisture amongst others. Fuel is dynamic and it changes through time (daily, weekly, monthly, seasonally, annually, etc). Fuel type is a description of fuel itself, whereas fuel state is dependent on changing environmental conditions. There are three types of fuels:

Ground fuel: all combustible materials below the surface litter layer (i.e. duff, peat layers or living plant materials such as roots). Ground fires burn the subsurface organic fuels and typically result in a lot of smoldering combustion and less active flaming. Roots of overstory species may be killed because of prolonged high temperatures in the rooting zone.

Surface fuel: fuels on the ground (herbaceous plants, grass, shrubs, leaf and needle litter, moss, lichen, upper layer of duff and dead branch debris). Surface fires spread by combustion of surface fuels and only burn the lowest vegetation layer giving them low to moderate severity without extensive overstory vegetation mortality.

Aerial or crown fuel: crowns or canopy of trees and shrubs. Crown fires burn through the tree crowns but in most cases, the understory vegetation is also burned.

Fuel load (Weir 2009)

Fuel load is a measure of the potential energy that could be released by a fire. It is the total amount of flammable fuel for the surface area of the burn unit and is normally measured on a dry weight basis (kg/ha). It is not the total amount of vegetation in the burn unit but what is available to actually burn within the unit.

Fuel management (BC Wildfire Service and Martell 2015)

The process of modifying forest and range fuels to reduce the fuels available to burn in a wildfire event. This modification of flammable fuel complexes can involve thinning out of trees, pruning branches, prescribed fire use and other best practices. The primary objective is to manage hazardous wildland fuels in and around communities and out to the landscape level, in order to reduce the potential for loss of life, property, and infrastructure.

Initial attack (CIFFC 2003/Martell 2015)

The action taken to halt the spread or potential spread of a fire by the first fire fighting force to arrive at the fire (CIFFC 2003). The early stages of suppression and the resources that are allocated to the fire.

Prescribed fire (CIFFC 2003/Bureau of Land Management)

Any fire utilized for prescribed burning; usually ignited according to agency policy and management objectives. A prescribed fire may be defined as any fire ignited by management actions under certain pre-determined conditions to meet specific objectives related to hazardous fuels reduction or habitat improvement. Proper planning elements are identified and explained in the technically reviewed and approved prescribed fire plan.

Prescribed burning (CIFFC 2003) and prescribed fire (CIFFC 2003)

The knowledgeable application of fire to a specific land area to accomplish predetermined forest management or other land use objectives. (Synonym: Fire use). Prescribed fire is any fire utilized for prescribed burning; usually ignited according to agency policy and management objectives.

Values at risk (BC Wildfire Service/CIFFC 2003)

The specific or collective set of natural resources and anthropogenic improvements/developments that have measurable or intrinsic worth and that could or may be destroyed or otherwise altered by fire in any given area.

Wildland-Urban interface (WUI) (Haight et al. 2004, Evans et al. 2015, Government of BC 2015)

The WUI is where houses and fairly dense vegetation are both present. The WUI is often the focus of fire prevention and preparedness projects including fuel reduction in forests, fuel removal in the immediate vicinity of homes, and emergency evacuation planning. In the US, there are two types of WUI: interface (3 or more structures per acre with shared municipal services) and intermix (as sparse as one structure per 40 acres) (Evans et al. 2015). The WUI is also considered as any area where combustible vegetation is found adjacent to homes, farm structures, or other buildings and is within two kilometers of a community with a density of 6 to 250 structures per square kilometer (Government of BC 2015). Recently introduced, the wildland industrial interface (WII) and an infrastructure interface are being considered in addition to the traditional WUI. Note: Johnston 2016.

Supporting references for the interaction of fire with wildlife adapted from Leverkus et al. 2017

Species	Habitat/vegetation type resource selection	Citation
Wood bison, *Bison bison athabascae*	Open rangeland/sedge meadows: foraging and wallowing	Soper 1941; Larter and Gates 1991; Harper and Gates 1999; Harper et al. 2000; Fortin et al. 2002; BC Ministry of Environment 2009a and 2009b; Goddard 2011
	Open forest: rutting, rubbing and foraging	Soper 1941; Larter and Gates 1991; Harper et al. 2000; Fortin et al. 2002
	Dense forest: cover, rubbing and forage	Soper 1941; Larter and Gates 1991; BC Ministry of Environment 2009a
	Muskeg/riparian areas: foraging and wallowing	Soper 1941; DeLong et al. 1991; Larter and Gates 1991; Harper et al. 2000; Fortin et al. 2002
Moose, *Alces alces andersoni*	Alpine	Meidinger and Lewis 1983; Gustine and Parker 2008; BC Ministry of Environment 2009a and 2009b
	Subalpine: winter use	BC Ministry of Environment 2009a and 2009b
	Open rangeland: forage	DeLong et al. 1991; Pojar and Stewart 1991a; Nappi et al. 2004; Fisher and Wilkinson 2005; Gustine et al. 2006b; BC Ministry of Environment 2009a; Goddard 2011
	Open forest	DeByle 1984; DeLong et al. 1991; Pojar and Stewart 1991a and 1991b; Fisher and Wilkinson 2005; BC Ministry of Environment 2009a and 2009b
	Dense forest: forage and thermal cover	DeLong et al. 1991; BC Ministry of Environment 2009a
	Muskeg/riparian: forage	DeLong et al. 1991; Pojar and Stewart 1991a; BC Ministry of Environment 2009a and 2009b
Woodland caribou, *Rangifer tarandus caribou*	Alpine: summer use and winter use	Seip and Bunnell 1985; Pojar and Stewart 1991b; Gustine et al. 2006a; Gustine and Parker 2008; BC Ministry of Environment 2009a and 2009b
	Subalpine	BC Ministry of Environment 2009a and 2009b
	Open rangeland	Pojar and Stewart 1991b
	Open forest	DeLong et al. 1991; Pojar and Stewart 1991a; Fisher and Wilkinson 2005; Dalerum et al. 2007; BC Ministry of Environment 2009a and 2009b
	Dense forest: winter use	DeLong et al. 1991; Fisher and Wilkinson 2005; Gustine et al. 2006a; Dalerum et al. 2007; Gustine and Parker 2008; BC Ministry of Environment 2009a and 2009b
	Muskeg/riparian	Pojar and Stewart 1991a; BC Ministry of Environment 2009a
Grizzly bear, *Ursus arctos*	Alpine: root digging	Meidinger and Lewis 1983; Pojar and Stewart 1991b; Munro et al. 2006; BC Ministry of Environment 2009a and 2009b
	Subalpine	BC Ministry of Environment 2009a and 2009b
	Open rangeland: root digging	DeLong et al. 1991; Pojar and Stewart 1991a; Pojar and Stewart 1991b; Gustine et al. 2006b; Munro et al. 2006; BC Ministry of Environment 2009a and 2009b
	Open forest: insect feeding and frugivory	Munro et al. 2006; BC Ministry of Environment 2009a
	Dense forest: selection for spruce forests	Ciarniello et al. 2007; BC Ministry of Environment 2009a
	Muskeg/riparian area	DeLong et al. 1991; Pojar and Stewart 1991a; BC Ministry of Environment 2009a and 2009b
Gray wolf, *Canis lupus*	Alpine	BC Ministry of Environment 2009a and 2009b
	Subalpine	BC Ministry of Environment 2009a and 2009b
	Open rangeland	DeLong et al. 1991; Pojar and Stewart 1991a; Fisher and Wilkinson 2005; Gustine et al. 2006b; BC Ministry of Environment 2009a and 2009b
	Open forest	DeLong et al. 1991; Pojar and Stewart 1991a; BC Ministry of Environment 2009a and 2009b
	Dense forest	DeLong et al. 1991; BC Ministry of Environment 2009a and 2009b
	Muskeg/riparian area	DeLong et al. 1991; Pojar and Stewart 1991a; BC Ministry of Environment 2009a and 2009b
Wolverine, *Gulo gulo*	Alpine: denning and rearing kits	Lofroth and Krebs 2007
	Subalpine: summer use	Krebs et al. 2007
	Open rangeland: dispersal corridors	Pojar and Stewart 1991a; Dalerum et al. 2008
	Open forest: dispersal corridors, winter use	Pojar and Stewart 1991a; Krebs et al. 2007; Dalerum et al. 2008
	Dense forest	DeLong et al. 1991
	Resource selection linked to availability and distribution of food resources	Hatler and Beal 2010
Fisher, *Martes pennanti*	Open rangeland: foraging	Fisher and Wilkinson 2005; Hatler and Beal 2010
	Open forest: hunting	Boutin et al. 2003; Sullivan et al. 2006
	Dense forest: foraging, winter use	Boutin et al. 2003; Fisher and Wilkinson 2005; Sullivan et al. 2006; Hatler and Beal 2010
	Muskeg/riparian area: foraging	Hatler and Beal 2010

From Leverkus *et al.* 2017.

Prescribed Fire Complexity Worksheet & Rating Guide

Complexity Element	Weighting Factor	Complexity Factor	Total Value
Safety	5		
Threats to Boundaries	5		
Fire Behaviour	5		
Objectives	4		
Size of Burn Organization	4		
Improvements within Burn Area or Adjacent to Burn Area	3		
Environmental/Timber/Cultural or Social Values	3		
Air Quality Values/Issues	3		
Logistic Considerations	3		
Political Considerations	2		
Tactical Operations	2		
Multiagency Involvement	1		
Project Total			

Type III Burn Boss Required for Projects with Rating of 40 - 51
Type II Burn Boss Required for Projects with Rating of 52 - 84
Type I Burn Boss Required for Projects with Rating of >84

The Prescribed Fire Complexity Analysis provides a method to assess the complexity of the planned prescribed fire project. The analysis incorporates an assigned numeric rating complexity value for specific complexity elements that are weighted in their contribution to overall complexity.

The weighted value is multiplied by the numeric rating value to provide a total value for that element. All elements are then "added to generate the total project complexity value. Breakpoint values are provided for low & moderate and high complexity elements." This complexity worksheet is accompanied (on the following pages) by a guide to numeric values for each complexity element shown.

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Guide to Numeric Rating

Complexity Element	1	2	3
Safety Weighting Factor 5	Safety issues are easily identified and mitigated.	Number of significant safety issues have been identified. All safety hazards have been identified on the LCES worksheet and mitigated.	Complex safety issues exist No vehicle access or remote access only.
Threats to Boundaries Weighting Factor 5	FFMC of 80 - 85 Low threat to boundaries. Low risk of spotting. Boundaries naturally defensible.	FFMC of 86 - 90 Moderate threat to boundaries. Moderate risk of spotting. Boundaries need modification to strengthen fuel breaks, lines etc.	FFMC of > 90 High threat to boundaries. High risk of spotting. Boundary modification necessary to compensate for continuous fuels.
Fire Behaviour,Wx,Fuel & Topog. Weighting Factor 5	Low variability in slope or aspect. Wx uniform & predictable. Surface fuels only (grass,needles) Uniform fuel type/load. No drought conditions present.	Moderate variability in slope or aspect. Wx variable but predictable. Ladder fuels present. Moderate variability in fuel type or loading. BUI indicates normal to moderate drought conditions exist.	High variability in slope or aspect. Wx variable & difficult to predict. Highly variable fuel types or loading. BUI indicates severe drought conditions exist. Altered fire regime, hazardous fuel or stand density conditions exist. Extreme fire behaviour potential.
Objectives Weighting Factor 4	Maintenance objectives Easily achieved objectives. Broad prescription.	Restoration objectives Reduction in both live & dead fuels Objectives judged to be moderately hard to achieve. Objectives may require moderately intense fire behaviour.	Restoration objectives in altered fuel situations. Precise treatment of fuels & multiple ecological objectives. Conflicts between objectives & constraints. Requires high intensity fire or a combination of fire intensities that are difficult to achieve.

Size of Project Organization Weighting Factor 4	Single resource project < 12 people on site.	Multiple resource project 13 - 24 people on site. Short term need for specialized resources.	Multiple branches, divisions or groups. > 24 people on site. Specialized resources required to accomplish objectives.
Improvements Weighting Factor 3	Very little risk to people or property or improvements within or adjacent to project.	Several values to be protected Mitigation through planning and/or preparations is adequate. May require some commitment of specialized resources.	Numerous values and/or numerous values to be protected. Severe damage likely without commitment of specialized resources with appropriate skill levels.
Timber/Natural/Cultural & Social Values Weighting Factor 3	Very little risk to values within or adjacent to project.	Several values to be protected Mitigation through planning and/or preparations is adequate. May require some commitment of specialized resources.	Numerous values and/or numerous values to be protected. Severe damage likely without commitment of specialized resources with appropriate skill levels.
Air Quality Weighting Factor 3	Few smoke sensitive areas near project. 95% Smoke is produced for less than 1 burning period. No potential for scheduling conflicts with other agencies.	Multiple smoke sensitive areas, but smoke impact mitigated in plan. 95% Smoke produced for 2 - 4 burning periods. Low potential for scheduling conflict	Multiple smoke sensitive areas with complex mitigation actions required. 95% Smoke produced longer than 4 days. Class 1 smoke sensitive areas. High potential for scheduling conflict
Logistics Weighting Factor 3	Easy Access Less than 4 day project, not including patrol status.	Difficult Access Support required for 4 - 10 days. Logistics Officer required. Anticipated difficulty in obtaining resources.	No vehicle or remote access only. Duration of project is greater than 10 days. Large logistics section required. Remote camps.
Political Considerations Weighting Factor 2	Minimal impact on neighbours or visitors. Minimal controversy. Minimal media interest.	Some impact on neighbours or visitors. Some controversy but mitigated. Press release or communications plan required	High impact on neighbours or visitors. High internal or external concerns Media present during operations, media contact on site.

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Tactical Operations Weighting Factor 2	Simple ignition pattern. Single ignition method. Holding requirements minimal.	Multiple ignition methods or sequences. Use of specialized ignition methods. Holding actions required to check, direct, or delay fire spread. Simultaneous use of hand and aerial ignition methods.	Complex ignition patterns. Simultaneous use of multiple ignition patterns or methods. Success of actions critical to accomplishment of objectives. Aerial support for mitigation actions desirable or necessary.
Multiagency Coordination or Involvement Weighting Factor 1	No major involvement with other agencies. No major concerns	Simple joint agency project. Some concerns.	Complex multiagency project. High Concerns