APPENDIX 16-E

Wildfire Burn Probability Analysis

Coffee Gold Project

WILDFIRE BURN PROBABILITY ANALYSIS

OF THE

FORTYMILE CARIBOU HABITAT SURROUNDING THE PROPOSED COFFEE GOLD PROJECT

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Submitted by

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EXECUTIVE SUMMARY

The Burn-P3 (Probability, Prediction and Planning) program developed by the Canadian Forest Service (CFS) is a simulation model that evaluates the fire likelihood or burn probability (BP) of a large fire-prone landscape and produces a spatially explicit estimate of wildfire susceptibility.

The objective of this project is to provide spatially explicit estimates of burn probability (%) and average head fire intensity (kW/m) of the study area that encompasses the Fortymile Caribou Study Area for the Coffee Gold project.

The primary output produced by the Burn-P3 model, given the regionally specific fuel, topography and historical weather information, is the burn probability map which indicates areas where wildfires are most likely to occur on the landscape. A secondary output produced by the Burn-P3 program is a fire intensity map which highlights the areas where the potential for extreme fire behaviour is most likely to occur on the landscape.

The tables below show the range of burn probability (%) and fire intensity (kW/m) that were calculated for this study area along with the associated report figure and page numbers.

Burn Probability (%)					
	Average	**99th Percentile**	**Maximum**	**Figure Number**	**Page Number**
Baseline (2015)	0.38	2.85	4.33	7	18

Fire Intensity (kW/m)					
	Average	**99th Percentile**	**Maximum**	**Figure Number**	**Page Number**
Baseline (2015)	1 257	15 855	92 494	10	21

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Kaminak Gold Corporation (Kaminak) is proposing to develop the Coffee Gold Project (the Project) which is located approximately 130 km south of Dawson City, Yukon. The Project proponent is required to submit a Project Proposal to the Yukon Environment and Socio-economic Assessment Board that includes an assessment of potential effects to valued components that may occur as a result of the Project. Wildlife habitat including that of the Fortymile caribou herd is one such valued component. As a component of the potential effects assessment, it is recognized that wildfire risk may have an influence on habitat quality and quantity for the Fortymile caribou herd.

In order to quantify this wildfire risk, the Burn-P3 model (Parisien *et al.*, 2005) was selected to create a wildfire risk map for the study area. The results of the wildfire risk assessment will be incorporated into the Fortymile caribou potential effects assessment to identify potential interactions between Project infrastructure and operations, wildfire risk and wildlife habitat.

The Burn-P3 program utilizes the Prometheus wildfire growth modeling program for all of the fire simulations. A detailed description of both the Burn-P3 and Prometheus programs (including links to additional information) are included in Appendix 1.

The purpose of this report is to document the methodology and results of the Burn-P3 Baseline (2015) wildfire risk analysis for the study area surrounding the Coffee Gold Project.

STUDY AREA

The study area encompasses an area of approximately 77 500 km^2 in central Yukon and includes the Fortymile Caribou Study Area for the Coffee Gold Project which was delineated in consultation with Yukon Environment based on the current distribution of the herd in Yukon and historic distributions. The study area for this project along with a 25 km buffer is shown in Figure 1.

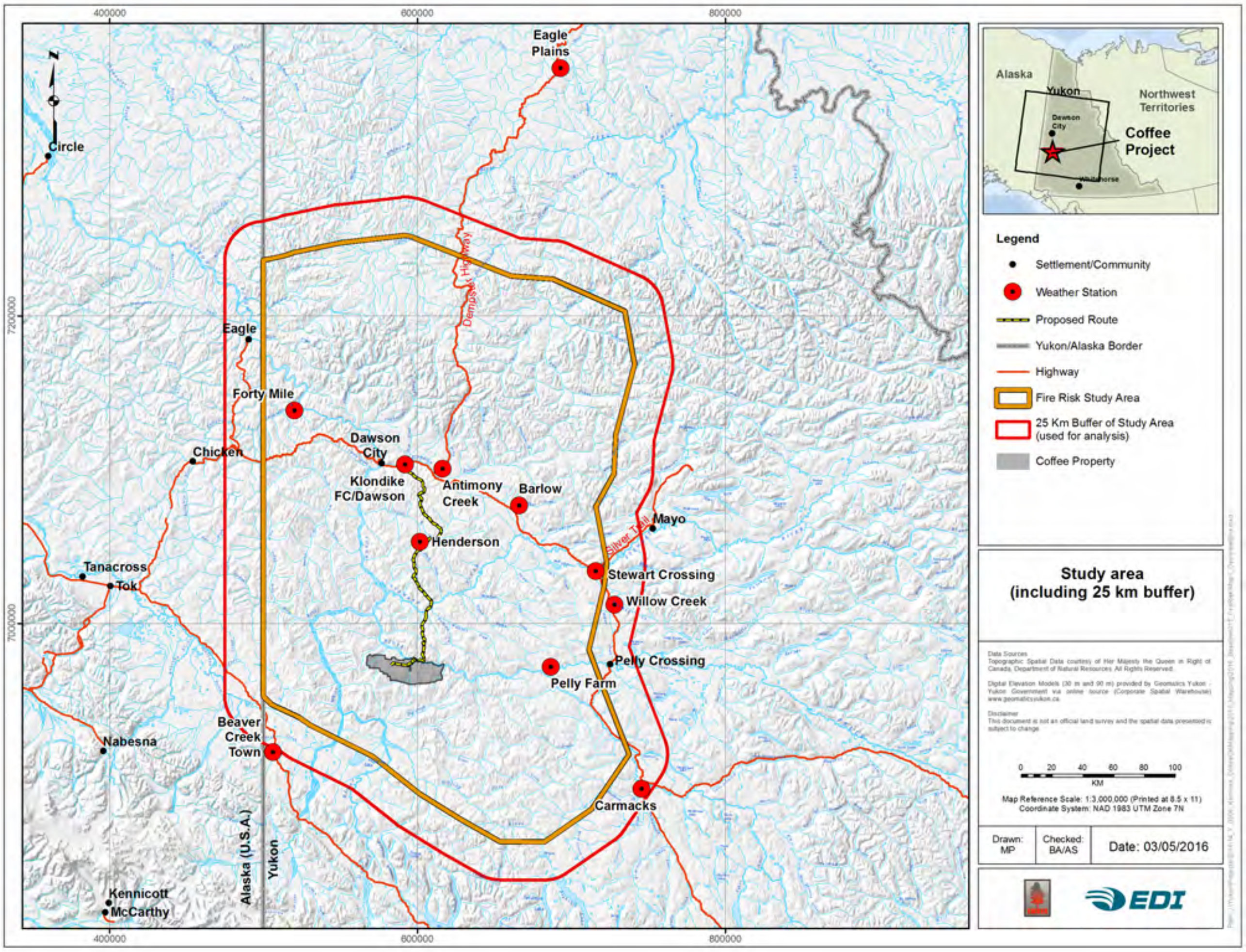

Figure 1. Study area map.

METHODOLOGY

BURN-P3 PROGRAM

For this analysis, Burn-P3 Version 4.5.19 (March 16, 2016) was used along with Prometheus version 6.2.1.11 (March 29, 2016). The Burn-P3 program settings used for this Yukon study area are described in detail within Appendix 2.

LANDSCAPE GRIDS

The Burn-P3 program requires the following landscape grids as data inputs to the program:

- Fire Behavior Prediction (FBP) System fuel type grid
- Elevation grid
- Weather zone grid
- Fire zone grid

All grid files use the Yukon Albers projection. Table 1 describes the parameters for these landscape grid files.

Table 1. Landscape grid parameters for study area.

				Yukon Albers Projection			
	Total area (Mha)	Cell Size (m)	Columns / Rows	Top	Left	Right	Bottom
Baseline (2015) Analysis	10.76	250 x 250	1858 / 2055	1286826.30865	-38492.952419	426007.047581	773076.308649

Note that each of these landscape grids includes a 25 km buffer around the study area boundary (Figure 1) to allow the Burn-P3 program to simulate fires that spread both into and out of the study area without restriction.

FBP System Fuel Type Grid

The FBP System fuel types for this project was obtained from the Northern Forestry Centre, Canadian Forest Service (CFS), Edmonton Alberta. Version 4.4 of the National FBP System fuel type map was provided in 250m x 250m grid cell resolution for the Yukon Territory and consists of fuel types derived from the Land Cover Time Series land cover map of Canada.

The following study area specific modifications to the FBP System fuels map were necessary for this Burn-P3 analysis :

1. Since Version 4.4 of the National FBP System fuel type map used for this study does not contain information about recent fire activity on the landscape, all fires within the historical fire database 10 years old or younger were classified as non-fuel. The decision to re-classify recent fires ≤ 10 years old to non-fuel was made following consultation with the following experts :

    Mr. Brian Simpson (Forest Analyst and Modeller, NoFC, CFS, Edmonton, AB) indicated that, although version 4.4 of the National FBP System fuels database was released in 2015, the actual imagery that was used to generate version 4.4 of the fuels map is older than 2015. Therefore , recent disturbances on the landscape (such as fires) will not show up as non-fuel. (personal communication, April 20, 2016).

    Mr. Al Beaver (Manager Science and Planning (retired), Wildland Fire Management) confirmed that a 10 year timeframe for a fuel re-classification was reasonable, while at the same time, indicating that there will be variation throughout the study area and sites where a non-fuel status less than and greater than 10 years will exist (personal communication, April 25, 2016).

2. Based on consultation with Yukon Fire Management staff for the Burn-P3 Dawson Range Burn-P3 analysis project in 2014 (Ember Research Services, 2014), fuels that were classified Deciduous (D1) and located above 1,100 metres were re-classified to non-fuel. This same FBP System fuel type re-classification algorithm was applied to this current study area.

Maps showing the areas affected by these fuel type changes are provided in Appendix 3 and the final FBP System fuel type map used for this Burn-P3 analysis is shown in Figure 2.

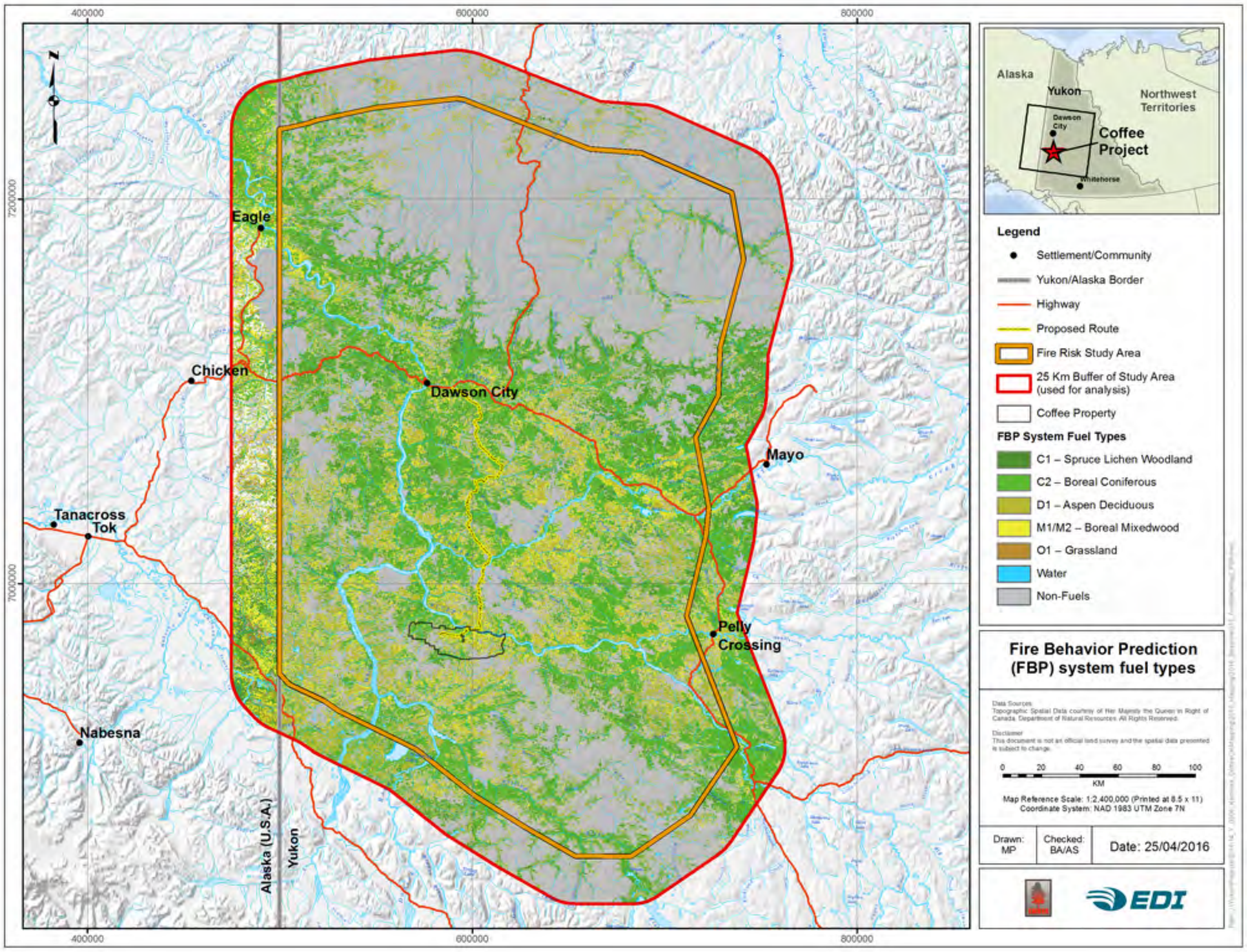

Figure 2. FBP System fuel type map.

The percentage of FBP System fuel types within the study area is shown in Table 2. A detailed description of each fuel type (including reference photographs) is included in Appendix 5.

Table 2. Area and percentage of Fire Behavior Prediction (FBP) System fuel types present in the study area.

FBP System fuel type code	FBP System fuel type name	Area (Mha)	Percentage of study area
C1	C1 Spruce-Lichen Woodland	**0.63**	**5.9**
C2	C2 Boreal Spruce	**1.69**	**15.6**
C3	C3 Mature Jack or Lodgepole Pine	**1.11**	**10.3**
C4	C4 Immature Jack or Lodgepole Pine	**0.05**	**0.5**
C7	C7 Ponderosa Pine - Douglas-fir	**0.16**	**1.5**
D1/D2	D1/D2 Aspen	**0.93**	**8.6**
M1/M2	M1/M2 Boreal Mixedwood	**0.90**	**8.3**
M1/M2	M1/M2 Boreal Mixedwood	**0.17**	**1.6**
O1a	O1a Matted Grass	**0.06**	**0.6**
Non-fuel	Water	**0.12**	**1.1**
Non-fuel	Non-Fuel	**1.18**	**11.0**
Non-fuel	Vegetated Non-Fuel	**3.76**	**35.0**
	Totals	**10.76**	**100.0**

Elevation Grid

The elevation grid was created using the NTS DEM at 1:50,000 scale. This data was then transformed from geographic to Yukon Albers projection and re-sampled to a 250m x 250m grid cell size. The map in Figure 3 shows the elevation grid used for this Burn-P3 analysis and the range and quartiles of the elevation area displayed in Table 3.

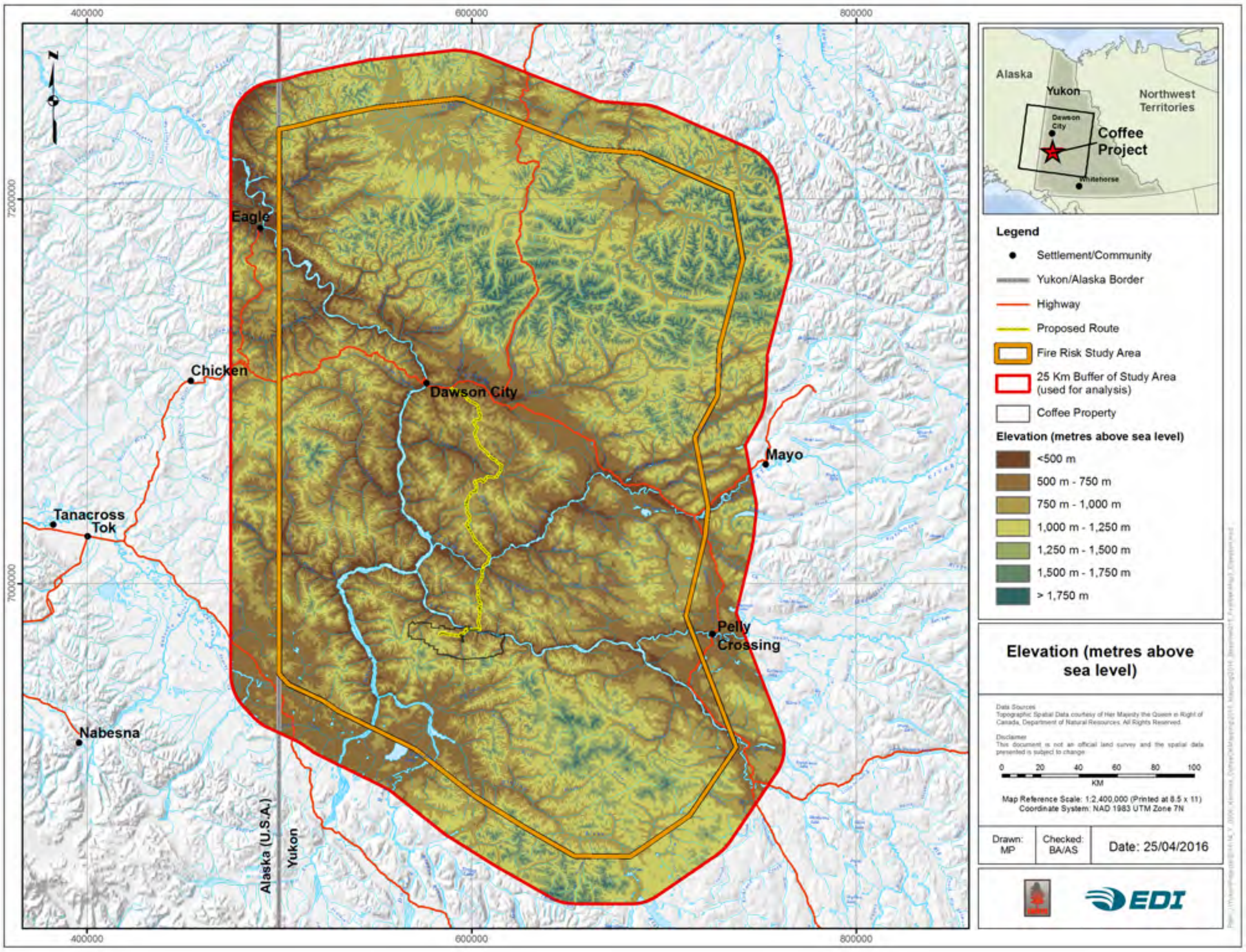

Figure 3. Elevation map.

Table 3. Elevation (metres) statistics for the study area.

	Minimum	25th Percentile	Median	Mean	75th Percentile	Maximum
Baseline (2015) Analysis	110	700	897	929	1 123	2 207

Fire/Weather Zone Grid

A total of seven weather zones were identified so that variations in weather patterns within study area could be accounted for with single or multiple weather station data where available and appropriate. These weather zones were defined with the assistance of local experts along with the most appropriate weather station(s) for each weather zone. The map in Figure 4 shows the seven weather zones defined and used for this study along with the weather station locations. Table 4 shows the percentage of the study area that is contained within each weather zone.

For the Burn-P3 analysis of this study area, fire zones were used to establish a geographical region where specific fire spread event distributions would apply. The fire zones used in this Burn-P3 analysis are the same as the weather zones described above and shown in Figure 4.

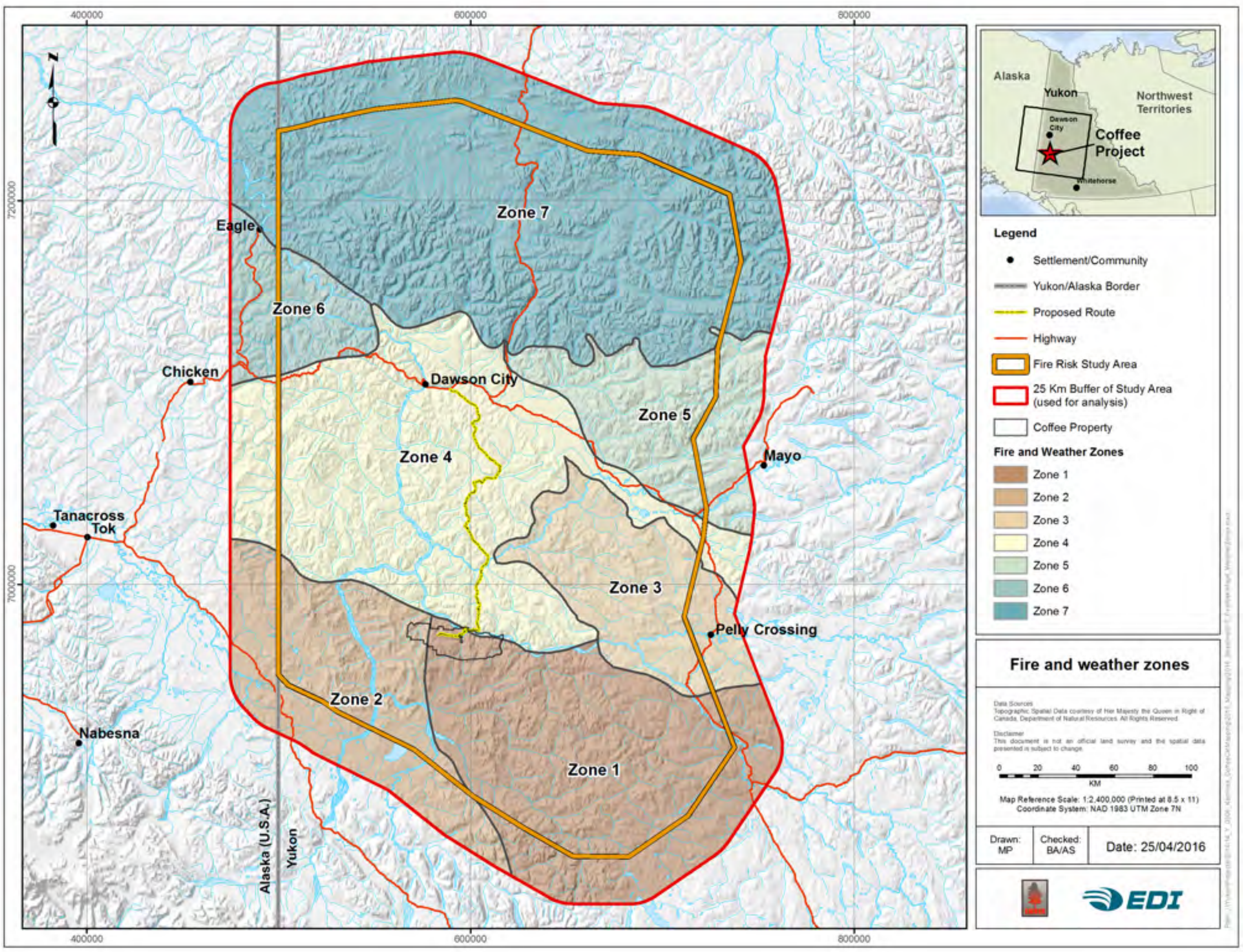

Figure 4. Fire/Weather zones map.

Table 4. Percentage of study area within each fire/weather zone.

Fire/Weather zone	Area (Mha)	Percentage of study area
1	1.86	17.3
2	1.12	10.4
3	0.82	7.7
4	2.35	21.8
5	0.78	7.3
6	0.44	4.1
7	3.39	31.4
Total	**10.76**	**100.0**

WEATHER DATA

The weather data used in this Burn-P3 analysis was provided by Micheal Smith, Chief Meteorologist, Yukon Wildland Fire Management.

The Burn-P3 program utilizes "daily" fire weather observations that reflect fire weather conditions that will result in a fire "spread-event" day. This current Burn-P3 analysis, used the same fire spread-event day criteria that was used in the (Ember Research Services, 2014) Dawson Range Burn-P3 analysis in 2014. Specifically, a fire spread-event day is any day where the Initial Spread Index (ISI) is greater or equal to 8.

The location and period of record of each weather stations used in this Burn-P3 analysis is shown in Table 5.

Table 5. List of weather zones and weather stations used in the Burn-P3 analysis.

Weather zone	Weather station	Latitude (º)	Longitude (º)	Elevation (m)	Period or record*
Weather zone 1	Carmacks	62.08	-136.29	600	1973-2015
Weather zone 2	Beaver Creek Beaver Creek Townsite	62.42 62.38	-140.87 -140.88	649 665	1969-2015 2007-2015
Weather zone 3	Pelly Farm	62.83	-137.33	445	1973-2015
Weather zone 4	Antimony Creek Dawson Henderson Stewart Crossing Willow Creek	64.01 64.05 63.59 63.37 63.17	-138.62 -139.13 -138.95 -136.68 -136.47	544 370 1009 500 800	2005-2015 1953-2015 1989-2015 1998-2015 1996-2015
Weather zone 5	Barlow	63.78	-137.63	759	1988-2015
Weather zone 6	Forty Mile	64.37	-140.58	562	2009-2015
Weather zone 7	Eagle Plains	66.31	-136.69	708	2010-2015

*Note that there are some breaks within the period of record for some weather stations.

Fire History Data

The Burn-P3 program utilizes data contained within the Yukon fire history database in several ways including :

1. identifying areas of recent fire activity that require re-classifying to non-fuel on the FBP System fuel type map (See Figure A3.2);
2. determining the distribution of escaped fires (ignitions) to simulate on the landscape for each iteration (year) of the simulation (See Figure A2.1);
3. determining the escaped fire rates per fire zone (See Table A2.2);
4. determining the historical fire size distribution present in the study area to assist with the calibration of the Burn-P3 model (See Figures 6, A4.1, A4.2).

Figure 5 shows a map of the historical fires that are contained within the Yukon fire history database for this study area.

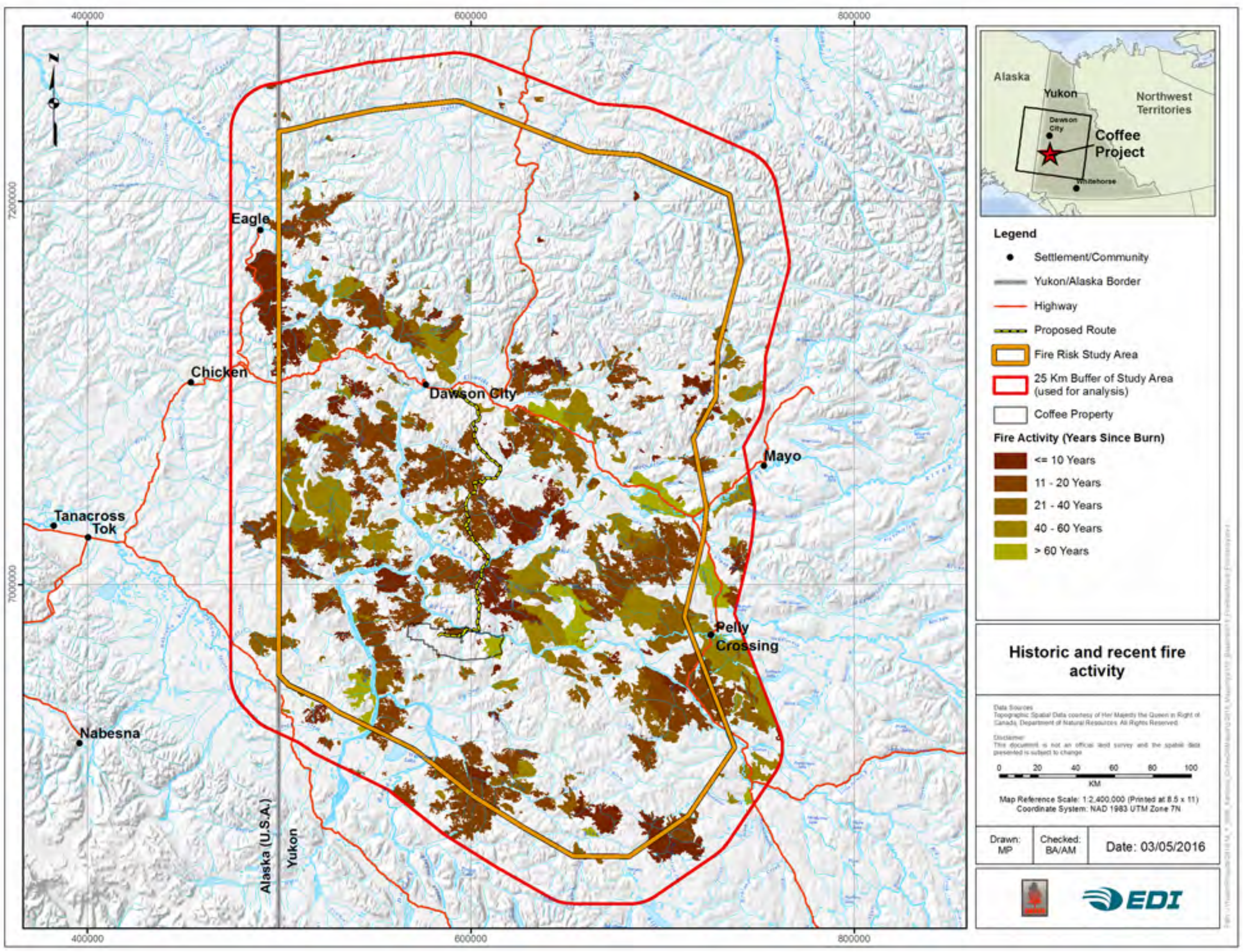

Figure 5. Fire history map.

Burn Probability Calculations

Baseline (2015)

The burn probability (%) results generated by the Burn-P3 program are calculated on a grid cell basis by adding up the number of times an individual cell burned and then dividing by the number of iterations completed during the Burn-P3 analysis - and then multiplying by 100 to get the results in percent.

Cumulative Burn Probability over the next 25 years and 50 years

Using Baseline (2015) results, it is possible to calculate the cumulative burn probability of the study area landscape – which is the probability that each individual grid cell or pixel on the landscape will burn sometime between now and some date in the future. In order to calculate this 'cumulative' burn probability for a given time period, the first step is to use the Burn-P3 model to determine the burn probability of the landscape as it currently exists – in this case, as of the conditions present in 2015 (Baseline 2015). The next step is to then apply the following equation to the burn probability grid produced by Burn-P3 in order to adjust for *t* number of years out in the future.

$$BP_t = 1 - (1-BP)^t$$

Where :

BP = Burn Probability of a landscape grid cell
t = number of years

Here is an example of how this approach would work for a 25 year time frame:

BP for a given grid cell on the landscape = 0.0235 (or 2.35%)
$BP_{25} = 1- (1-0.0235)^{25}$
= 0.4482 or 44.8 % chance of burning within 25 years

Here is an example of how this approach would work for a 50 year time frame:

BP for a given grid cell on the landscape = 0.0235 (or 2.35%)
$BP_{50} = 1- (1-0.0235)^{50}$
= 0.6954 or 69.5 % chance of burning within 50 years

Note that this simplistic approach to estimating the cumulative burn probability into the future does not take into account changes in the weather and fuels that are expected to occur as a result of climate change - which would influence future burn probabilities.

RESULTS

The Burn-P3 is designed to simulate a very large number of fires on the study area landscape. Table 6 shows the number of iterations, the number of simulated fires and the density of simulated fires used in the Burn-P3 analysis of the current study area.

Table 6. Number of iterations, simulated fires and simulated fire density completed during the Burn-P3 analysis.

	Number of Iterations	Number of Simulated Fires	Density of Simulated Fires (number of fires per 100 ha of burnable fuel)
Baseline (2015) Analysis	95 623	944 869	16.6

CALIBRATION

Calibration of the Burn-P3 model is required to ensure that the burn probability values produced by the model are as accurate as possible for the combination of weather, topography and fuels that varies across the study area landscape. The calibration of the Burn-P3 model involves the adjustment of model parameters until the simulated fire size distribution and the number of simulated fires per year are similar (and as close as possible) to the values present within the historical fire database for the study area.

The number of fires per year, area burned per year and fire size statistics are displayed in Table 7. In addition, Figure 6 shows how the fire size distribution compares between the Burn-P3 simulated fires and the historical database fires as well as how the percentiles of the log fire sizes compare for each fire/weather zone. The results of the calibration process for this study area are consistent with other Burn-P3 studies completed in the Yukon and NWT. More results of the calibration process are included in Appendix 4.

Table 7. Average number of fires and average area burned per year.

	Fire History Database[1]	Burn-P3 Simulations[1]	Difference (%)
Number of Fires per year	9.9	9.9	0.0
Area Burned (ha) per year	41 989	39 763	5.4
Median Fire Size (ha)	560	506	10.1
Mean Fire Size (ha)	4 163	4 024	3.4
Maximum Fire Size (ha)	128 637	145 988	12.6

Note 1: only fires >= 30 ha are included in the statistical calculations

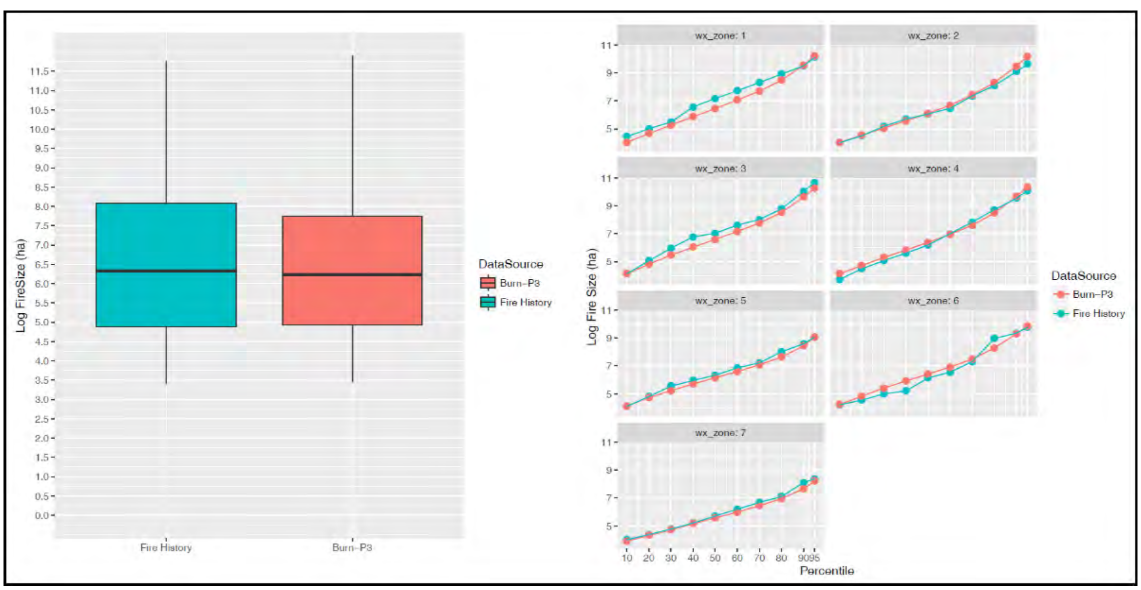

Figure 6. Comparisons of Log fire sizes (fire history database vs. Burn-P3 simulated fires).

BURN PROBABILITY

The Burn-P3 model is designed to evaluate the relative likelihood of burning or burn probability (BP) at every given point (i.e., pixel) on a rasterized landscape. This objective is achieved by modeling the ignition and spread of individual wildfires greater or equal to a pre-determined size. The minimum fire size established for this study area was 30 ha.

The maps indicating the burn probability in 2015 and the cumulative burn probability in 25 and 50 years into the future are shown in figures 7, 8, and 9 respectively.

Baseline (2015)

Table 8 shows the burn probability (%) statistics over the entire study area and the map in Figure 7 shows the spatial distribution of burn probability (%) values on the study area landscape.

Table 8. Burn probability (%) statistics for the study area.

	Minimum	Mean	99th Percentile	Maximum
Baseline (2015) Analysis	0.00	0.38	2.85	4.33

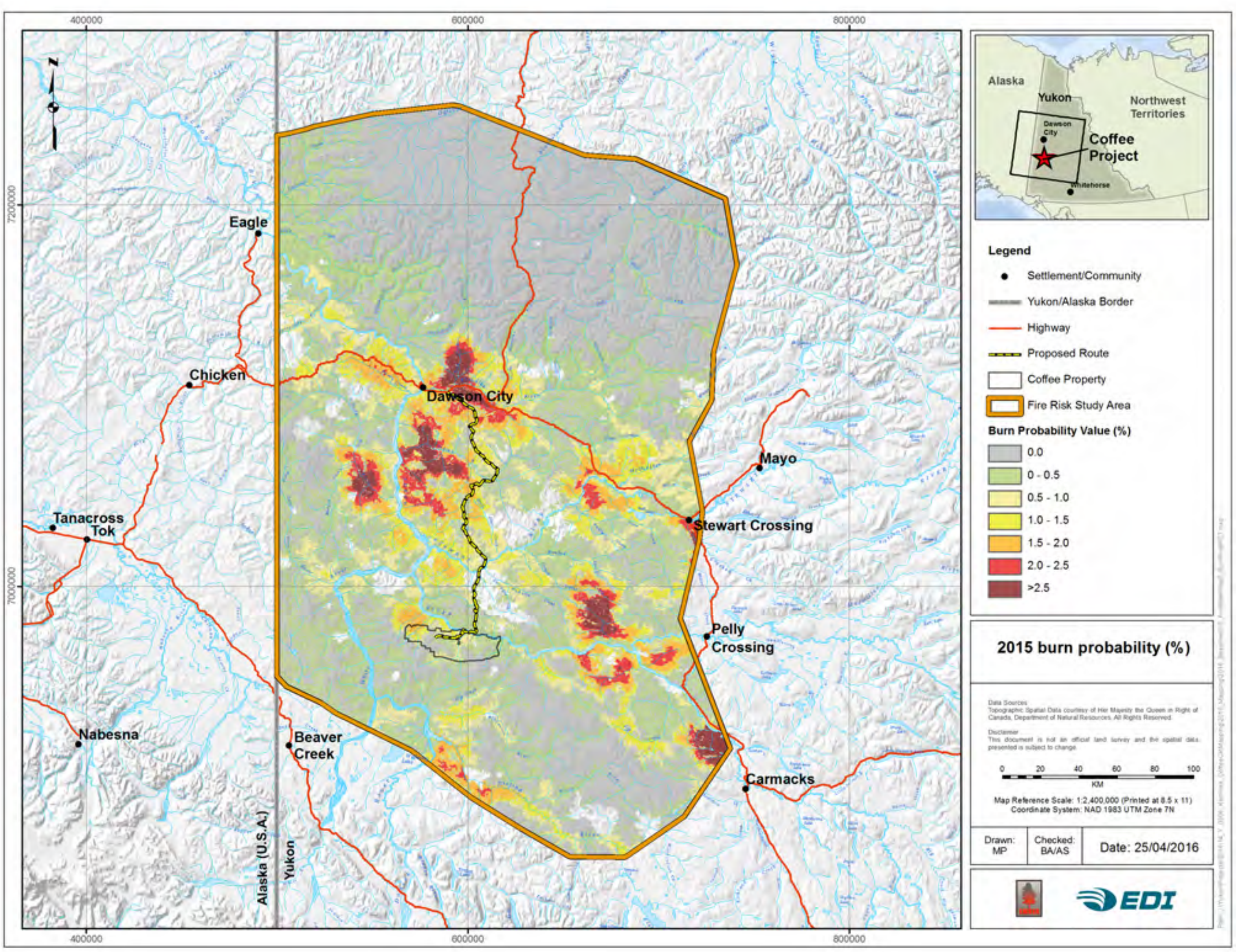

Figure 7. Burn probability (%) (2015) map.

Cumulative Burn Probability (%) over the next 25 years

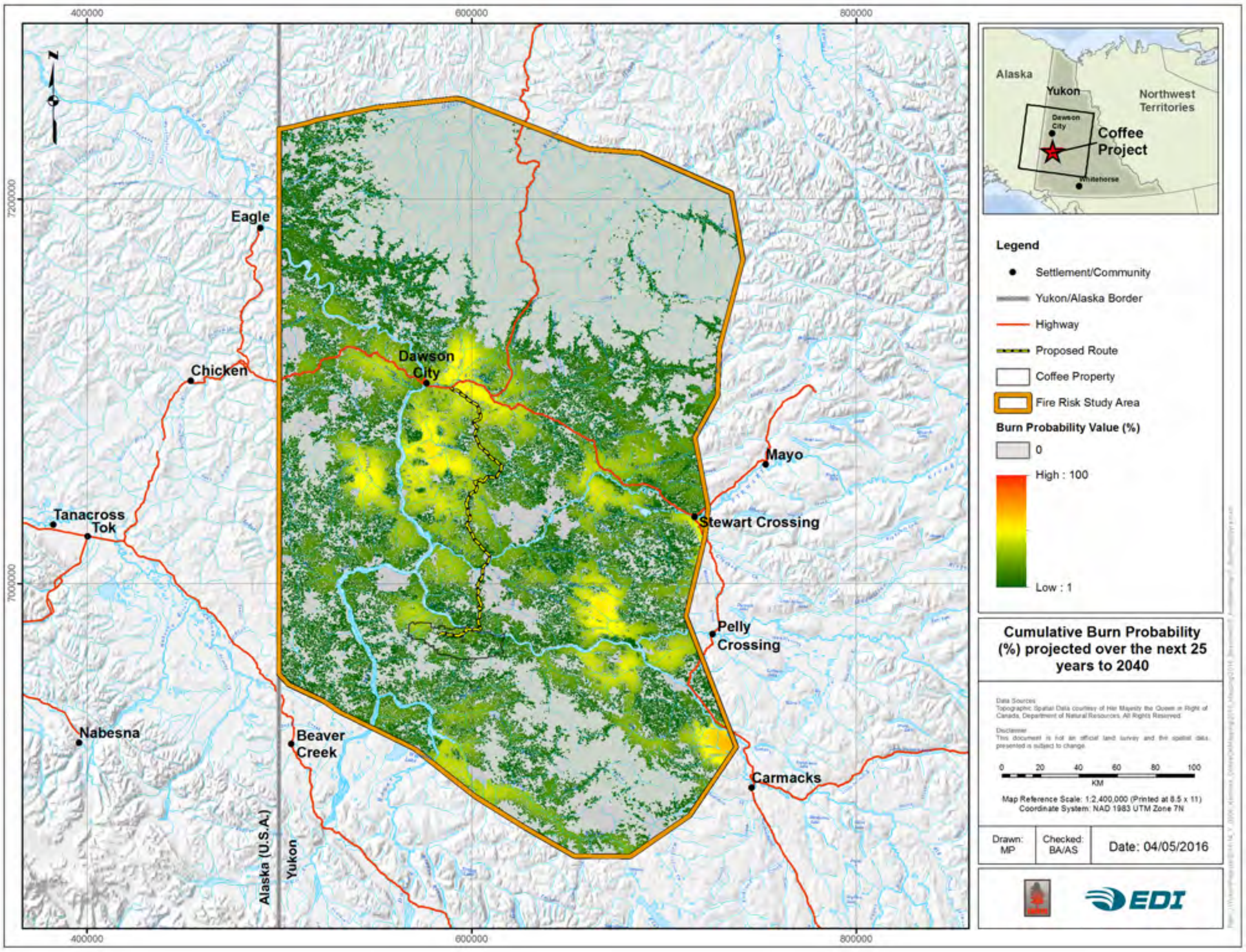

Figure 8. Cumulative burn probability (%) over the next 25 years to 2040.

Cumulative Burn Probability (%) over the next 50 years

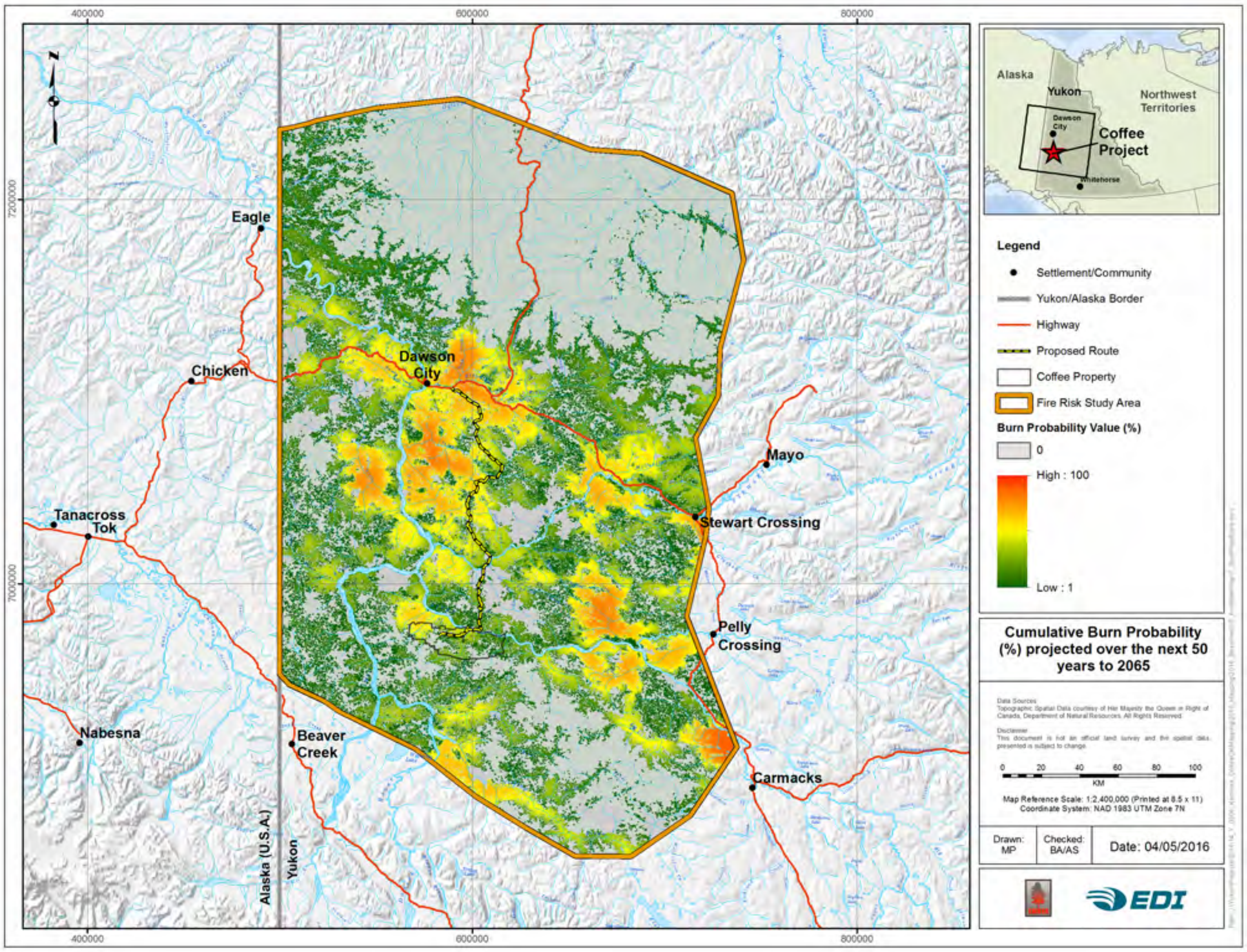

Figure 9. Cumulative burn probability (%) over the next 50 years to 2065.

FIRE INTENSITY

Fire intensity (kW/m) is one of the outputs generated by the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992) and available as an output variable in the Burn-P3 program. Fire intensity is defined as the rate of heat energy release per unit time per unit length of fire front and is based on Byram's (1959) formula for calculating fire intensity. The calculation of fire intensity for wildfires is described in detail by Alexander (1982).

The mean fire intensity (kW/m) was calculated for every every grid cell that burned during the Burn-P3 fire simulations. These mean fire intensity statistics are shown in Table 9. The map in Figure 10 shows the spatial distribution of the fire intensity values on the study area landscape.

Table 9. Fire intensity (kW/m) statistics for the study area.

	Minimum	Mean	99th Percentile	Maximum
Baseline (2015) Analysis	0.00	1 257	15 855	92 494

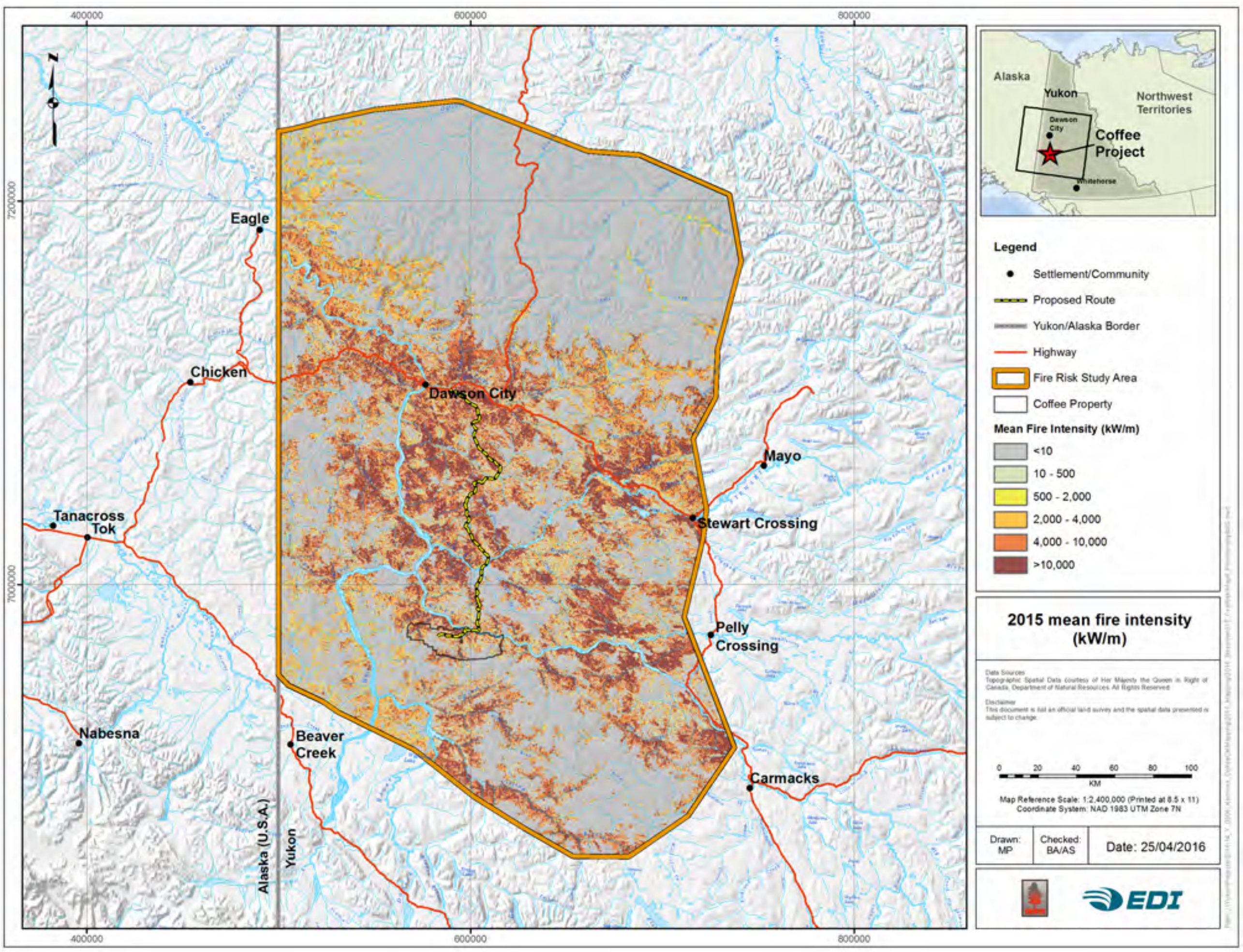

Figure 10. Mean fire intensity (kW/m) (2015) map.

DISCUSSION

CALIBRATION RESULTS

The calibration of the Burn-P3 model to a specific study area can be challenging depending on a number of factors such as the size and variability of the landscape, the ecosystem classifications and the associated fire history characteristics of these combination of factors. This particular study area is over 10 million hectares and is considered large for a Burn-P3 analysis. In addition, several of the weather zones have very different fire history characteristics. For example, fire/weather zones 1, 2, and 7 have a lower level of fire activity (see Figures 4 and 5) which is reflective of the combination of fuel types, topography and fire weather conditions.

However, despite the challenges of calibrating Burn-P3 over such a large and varied landscape, the results of the calibration process for this particular study area are actually very good. For example, as shown in Table 7, the number of fires per year are exactly the same for both the fire history database and the Burn-P3 simulated fires. In addition, the percent difference between the historical fire database and the Burn-P3 simulations ranges between 3.4 and 12.6 percent for a variety of fire related statistics.

The box plot in Figure 6 shows the results of the calibration process for this study area in terms of the differences between the logarithm of the fire sizes (ha) of the historical fires and the Burn-P3 simulated fires. Note that there is a slight difference between the medians (black horizontal line in the middle of the box) and a larger difference at the 75th percentile (top of the box).

The fire size distributions within each of the seven fire/weather zones may respond differently to changes in the various Burn-P3 model parameters and the art/science challenge is to find the optimal solution that minimizes the differences in fire size distribution across all fire/weather zones. The line plots in Figure 6 show how the percentile values of the logarithm fire sizes (ha) for the final calibration results vary between the historical fires and the Burn-P3 simulated fires for each of the seven fire/weather zones.

Some additional calibration results for this study area are shown in Appendix 4.

BURN PROBABILITY RESULTS

The burn probability map shown in Figure 7 shows distinct 'hot spots' of higher burn probability. Visual inspection of these burn probability indicates that these hot spots are well correlated with the large areas of the C2 (boreal spruce) fuel type that occurs throughout the study area.

The burn probability ranges from a minimum of 0% to a maximum of 4.33% as summarized in Table 8. Note that, technically, the maximum burn probability recorded in the study area was 4.33%; however, the 99th percentile value of the burn probability is 2.85%. These results indicate that only 1 % of the grid cells in the study area had a burn probability greater than 2.85%.

The burn probability results from this study area are similar to what was reported from the Burn-P3 analysis of the Dawson Range study area in 2014 (Ember Research Services, 2014). These results are not unexpected since this current study area completely encompasses the smaller 2014 Dawson Range study area. The average and maximum values of burn probability (%) from the 2014 were 0.427 and 2.6 respectively. In slight contrast, the average and 99th percentile values of burn probability (%) for the current study are 0.38 and 2.85, respectively.

As was discussed previously in the 2014 report, Burn-P3 simulates fires assuming the absence of fire suppression activity and this can lead to a possible over-estimation of burn probability in certain areas depending on the Yukon Fire Management Zone that the simulated fires fall into.

For example, the areas of relatively high burn probability around the village of Carmacks are within fire zones designated for active fire suppression – specifically the Critical Fire Management Zone and the Full Fire Management Zone (Yukon Fire Management, 2003). In addition, Carmacks is in close proximity to an attack base which is likely to provide effective suppression activity within the surrounding area. Therefore, the simulated fires generated by the Burn-P3 model are likely going to grow larger than fires starting in the same areas in real life due to these fires being subject to active fire suppression.

The 25 and 50 year cumulative burn probability maps (Figures 8 and Figure 9) show the same areas of relatively high burn probability and are also subject to the same cautionary notes about potential for over-estimation of burn probability depending on whether certain areas of the study area are subject to active fire suppression or not.

The burn probability estimates for 25 and 50 years into the future do not take into account any sort of climate change effect that might show up in the weather records for these time periods. Therefore it is reasonable to assume that the actual burn probabilities calculated with this study may be an over- or under-estimation of the actual burn probabilities. However, while the actual burn probability for a given pixel on the landscape may be an over- or under-estimate the relative difference of burn probabilities over the landscape is not likely to change from the Baseline (2015) burn probability map.

In addition to potential weather changes 25 and 50 years into the future, it is also important to remember that there are changes in fuel types that will occur moving into the future. In particular, old burn areas that are currently classified as grass fuel types (O1a and O1b) fuel types may eventually change into a forested fuel type such as spruce (C1,C2) or pine (C3,C4) or a mixedwood fuel type (M1, M2).

Fire Intensity Results

One of the outputs of the Burn-P3 program is the 'average fire intensity' measured in kW/m. For this particular study area, we have included a map of average fire intensity which is presented in Figure 10. The average fire intensity is calculated by tracking the fire intensity that occurs within each pixel or grid cell for every fire that burns that particular fuel grid cell. At the end of the simulation, the average fire intensity of all fires that burned each individual grid cell is calculated and recorded.

The fire intensity classes shown on the map are commonly used by fire agencies across the Canada to assist in the decision-making process of allocating appropriate fire suppression resources to a particular fire. For example, Alexander and Cole (1995) describe how fire suppression activity in C2 (boreal spruce) fuel types is dependent on the level of fire intensity. Appendix 6 contains a table from the Alexander and Cole (1995) report entitled “Description of Probable Fire Potential and Implications for Wildfire Suppression” which details the fire suppression response that is appropriate for each of the five fire intensity classes described.

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APPENDIX 1: BURN-P3 AND PROMETHEUS PROGRAM DESCRIPTIONS

Burn-P3 (Probability, Prediction, and Planning) is a simulation model that evaluates the fire likelihood or burn probability (BP) of a large fire-prone landscape. The model is packaged as a Windows-based software application that is available free of charge. It can be downloaded with documentation and test files from:
http://www.ualberta.ca/~wcwfs/burn-p3-en.html

The software was developed by Marc-André Parisien from the Canadian Forest Service (CFS), with the collaboration of Parks Canada, the Canadian Interagency Forest Fire Centre (CIFFC), the Canadian Boreal Forest Agreement (CBFA), the Province of Alberta, the Province of British Columbia, and the Province of Saskatchewan.

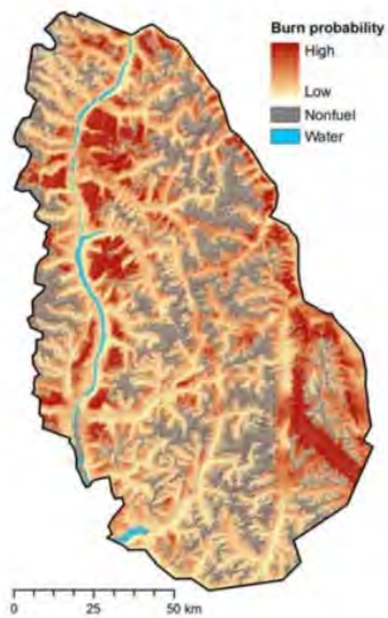
To create Burn-P3 inputs, the user must have some knowledge of raster-based geographic information systems (GIS) applications. Also, because Burn-P3 is largely based on the Canadian Forest Fire Danger Rating System (CFFDRS), the user is expected to be familiar with its two main sub-systems: the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Fire Behaviour Prediction (FBP) System (FCFDG 1992).

Familiarity with the Prometheus fire growth model is also highly recommended.

Burn-P3

Burn-P3 (probability, prediction, and planning) is a spatial fire simulation model that is used for land-management planning and wildland fire research. It uses the Prometheus fire-growth engine to simulate the ignition and spread of a very large number of fires. The inputs to Burn-P3 consist of fuels (e.g., vegetation), topography, weather, and patterns of fire ignitions. Its main output is a surface of fire probabilities, or burn probability map.

- Windows-based software application
- Computes burn probabilities for large landscapes
- Produces additional outputs, such as fire intensity maps
- Extracts fire statistics and simulated fire perimeters

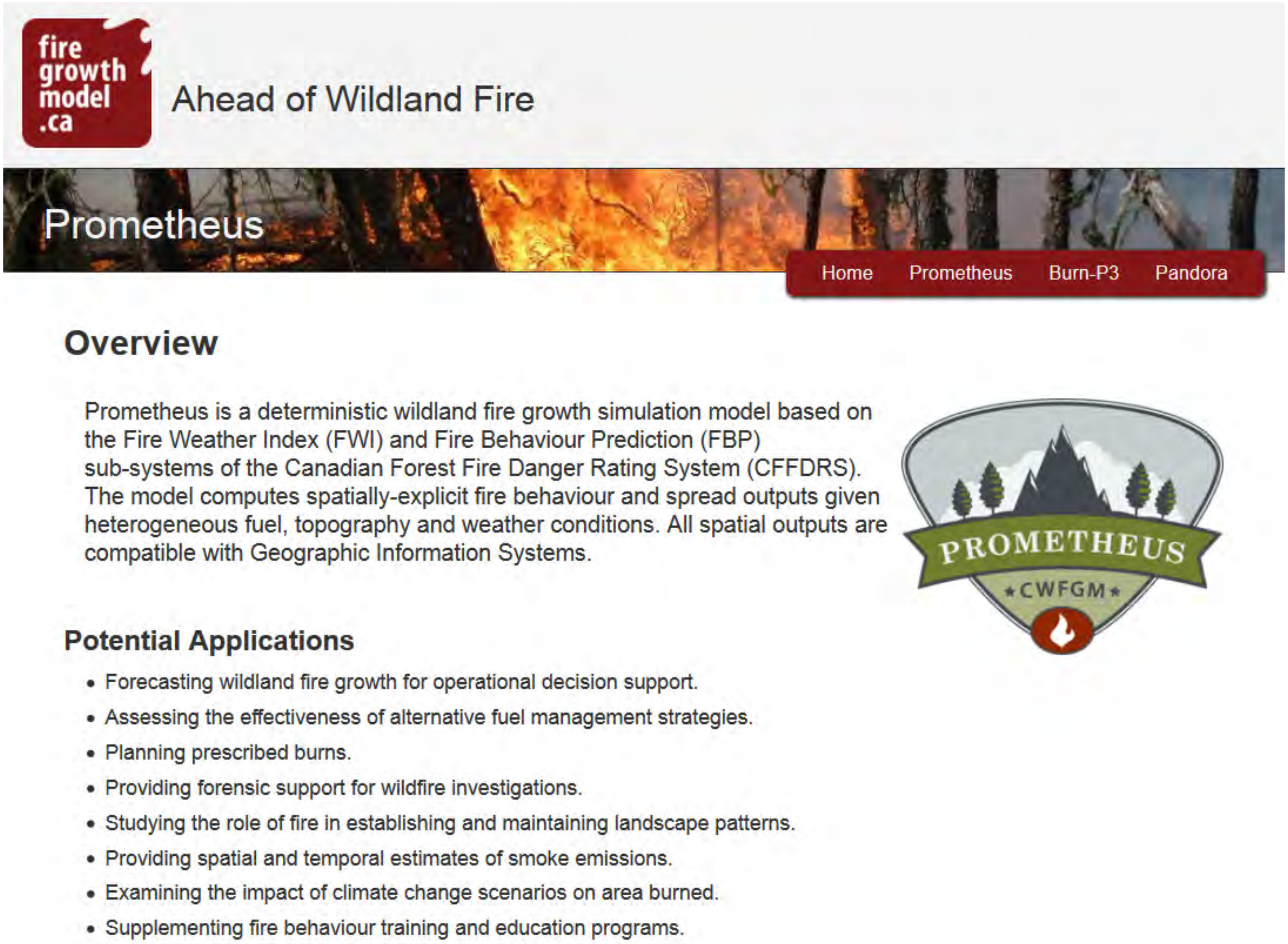


System Requirements

- Processor: Intel Core i3 or i5
- 4 GB of RAM
- 10 GB of available disk space
- 64-bit Windows operating system, Windows 7 (recommended), Windows 8, or Vista 64
- Most up-to-date version of the Prometheus fire growth model

Download Burn-P3 Version 4.3.4

Source: http://www.ualberta.ca/~wcwfs/burn-p3-en.html



fire growth model .ca

Ahead of Wildland Fire

Prometheus

Home Prometheus Burn-P3 Pandora

Overview

Prometheus is a deterministic wildland fire growth simulation model based on the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) sub-systems of the Canadian Forest Fire Danger Rating System (CFFDRS). The model computes spatially-explicit fire behaviour and spread outputs given heterogeneous fuel, topography and weather conditions. All spatial outputs are compatible with Geographic Information Systems.

PROMETHEUS
★CWFGM★

Potential Applications

- Forecasting wildland fire growth for operational decision support.
- Assessing the effectiveness of alternative fuel management strategies.
- Planning prescribed burns.
- Providing forensic support for wildfire investigations.
- Studying the role of fire in establishing and maintaining landscape patterns.
- Providing spatial and temporal estimates of smoke emissions.
- Examining the impact of climate change scenarios on area burned.
- Supplementing fire behaviour training and education programs.

Source: http://www.firegrowthmodel.ca/prometheus/overview_e.php

Technical Documentation

Tymstra, C.; Bryce, R.W.; Wotton, B.M.; Taylor, S.W.; Armitage, O.B. 2010. Development and Structure of Prometheus: the Canadian Wildland Fire Growth Simulation Model. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-417. 88 p. [PDF]

Source:
http://www.firegrowthmodel.ca/prometheus/downloads/Prometheus_Information_Report_NOR-X-417_2010.pdf

Selected References:

The Burn-P3 software official documentation:

Parisien, M. A., Kafka, V.G., Hirsch, K.G., Todd, B.M., Lavoie, S.G., and Maczek, P.D. 2005. Mapping fire susceptibility with the Burn-P3 simulation model. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Information Report NOR-X-405.

The Canadian Forest Fire Weather Index (FWI) System:

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35. Canadian Forest Service, Ottawa, ON. 48

Lawson, B.D.; Armitage, O.B., Weather Guide for the Canadian Forest Fire Danger Rating System. 2008., Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. 84 p

The Canadian Forest Fire Behaviour (FBP) System:

http://cwfis.cfs.nrcan.gc.ca/background/summary/fbp

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behaviour Prediction System. Forestry Canada, Fire Danger Group and Science and Sustainable Development Directorate, Ottawa 64 p.

Hirsch, K.G. 1996. Canadian Forest Fire Behavior Prediction (FBP) System: user's guide. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Spec. Rep. 7.

The Canadian Forest Service National Fire Database (NFDB)

Download: http://cwfis.cfs.nrcan.gc.ca/datamart

Parisien, M.A., Peters, V.S, Wang, Y., Little, J.M., Bosch, E.M., Stocks, B.J. 2006. Spatial patterns of forest fires in Canada 1980-1999. Int. J. Wildland Fire 15: 361-374.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D.,Hirsch, K.G., Logan, K.A., Martell, D.L., Skinner, W.R. 2002. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research 107: 8149 <doi:10.1029/2001 JD000484>

The Prometheus fire growth model

Download: http://firegrowthmodel.ca/

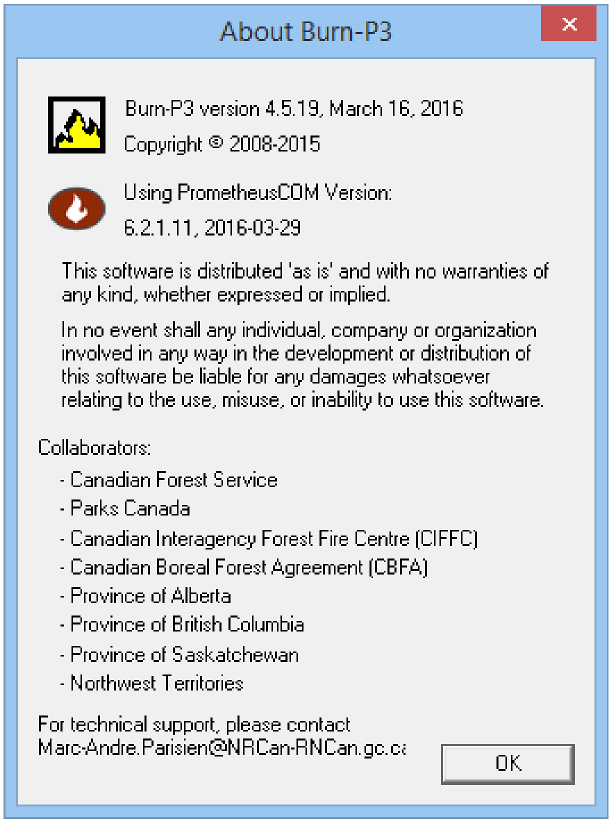
Tymstra, C., Bryce, R.W., Wotton, B.M., Taylor, S.W., Armitage, O.B. 2010. Development and structure of Prometheus: the Canadian Wildland Fire Growth Simulation Model. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-417. 102 p.

APPENDIX 2: BURN-P3 PROGRAM PARAMETERS

Program Versions

The following program versions were used for the Burn-P3 analysis documented in this report

- PrometheusCOM: 6.2.1.11 March 29, 2016
- Burn-P3 : 4.5.19 March 16, 2016



The Burn-P3 model has a large number of parameters to control the ignition, burning conditions and fire growth of simulated fires. Table A2.1 describes the Burn-P3 model parameters selected within each of the program's modules.

Table A2.1 Burn-P3 model parameters selected for use with this study area

Burn-P3 settings		Parameter	Note
Ignitions module	Ignition locations	Spatially random ignitions	
	Ignition rules	none	
	Distribution of escaped fires	Yes	See Figure A2.1
	Distribution of escaped fire rates	Yes	See Table A2.2
Burning conditions module	Fire weather list	YT historical weather ISI >=8	See Table 5
	Daily fire weather selection method	Random	
	Distribution of spread-event days (by weather zone)	Yes	See Figure A2.2
Fire growth module	Number of burning hours per day	Distribution	See Table A2.3
	Fires stop growing when encountering plot edge	no	
	Grass curing (%) (spring / summer)	100 / 80	
	Green-up (spring / summer)	OFF / ON	Median date: 05/01
Simulation	Length of run (number of iterations)	95 623	Total iterations from 4 computers
	Minimum fire size (ha)	30	
	Auto-save Burn-P3 outputs every (number of iterations)	100	
	Randomization control	Do a new run	

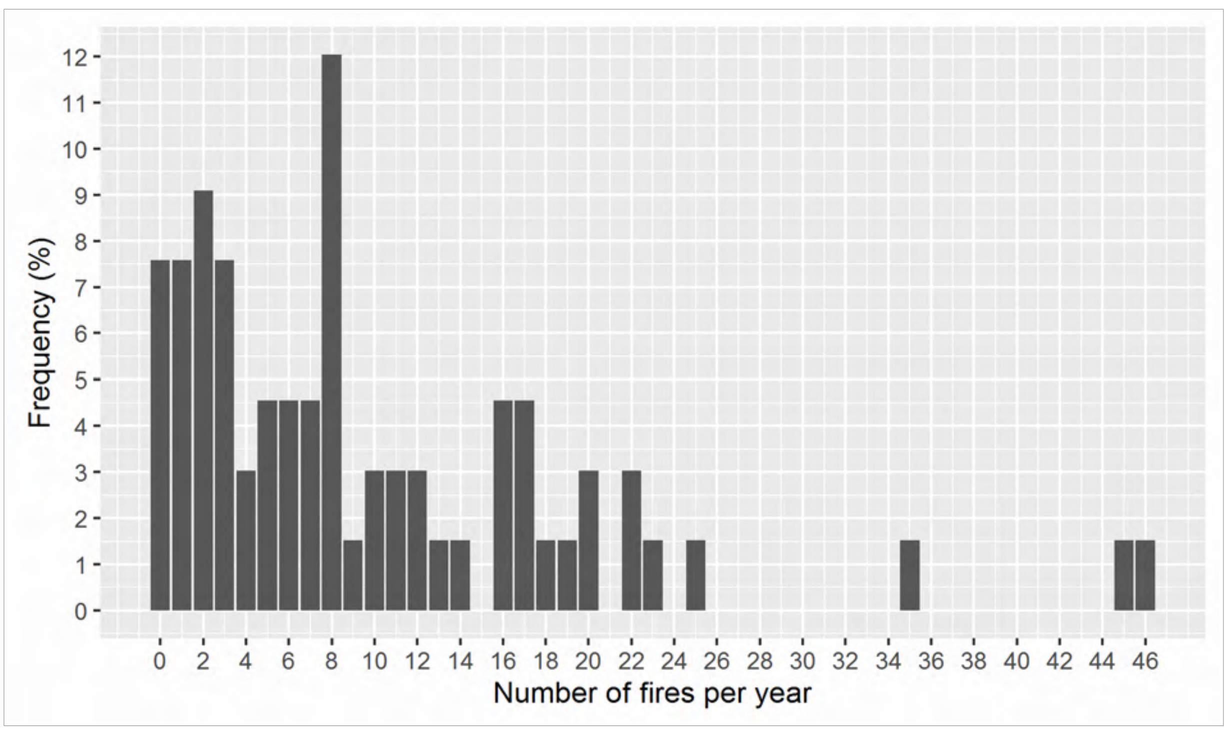


Figure A2.1 Distribution of escaped fires – Percentage of escaped fires per iteration (year).

Table A2.2 Distribution of escaped fire rates.

season	cause	Weather zone	Escaped fire rate
1	1	1	11.07
1	1	2	9.26
1	1	3	10.62
1	1	4	38.33
1	1	5	12.42
1	1	6	4.59
1	1	7	13.70
		total	100.00

Season 1 = 'Summer'; Cause 1 = 'Lightning'

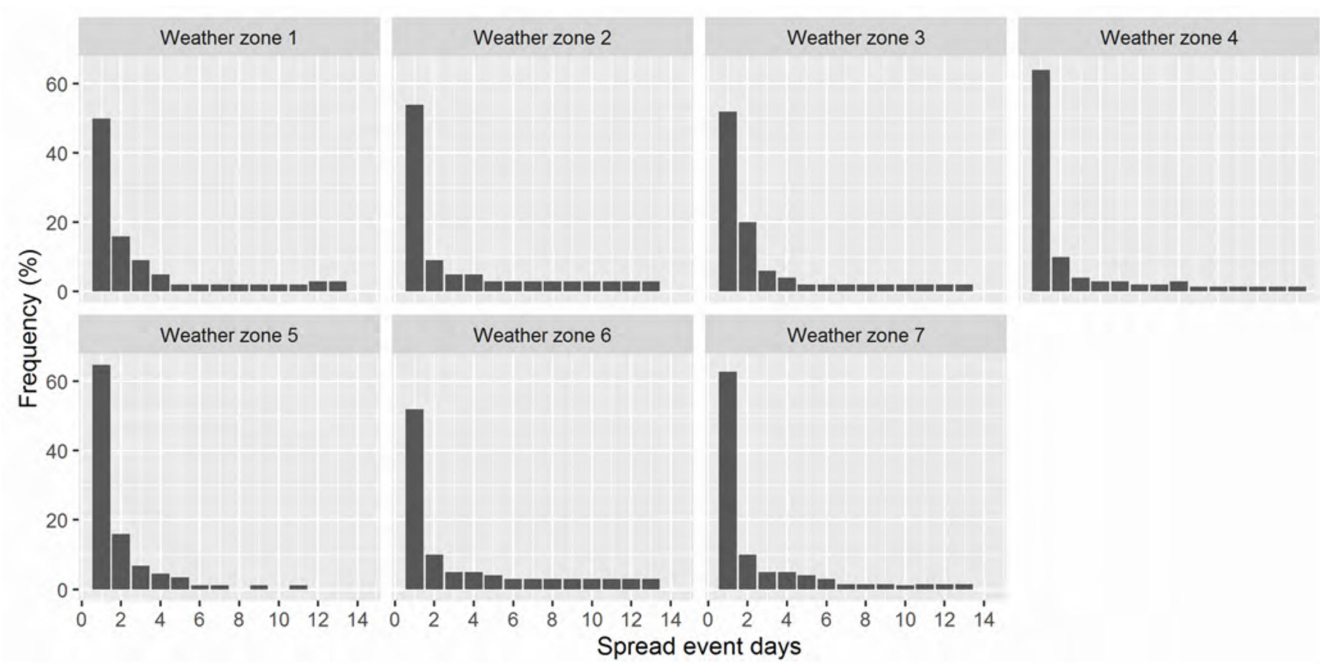


Figure A2.2 Distribution of spread-event days by weather zone.

Table A2.3 Distribution of burning hours per day.

Burning hours per day	1	2	3	4	5	6	7	8	9	10
Percent	10	10	10	10	10	10	10	10	10	10

APPENDIX 3: FUEL TYPE GRID MODIFICATIONS

Conversion of deciduous (D1) fuel type to non-fuel

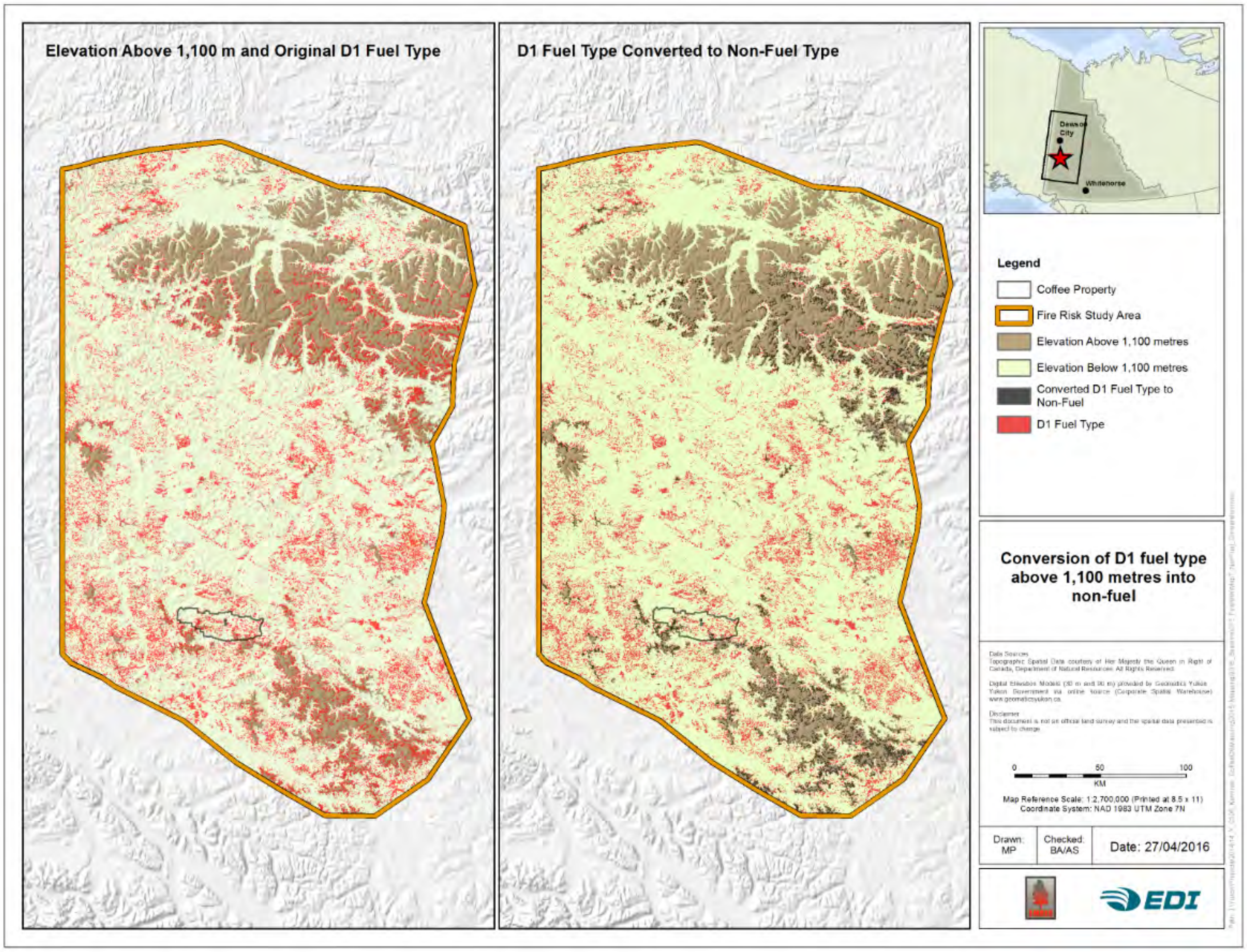


Figure A3.1. Map indicating the areas of D1 fuel type (above 1,100 metres) re-classified to non-fuel.

Conversion of areas of recent fire activity (≤ 10 years old) to non-fuel

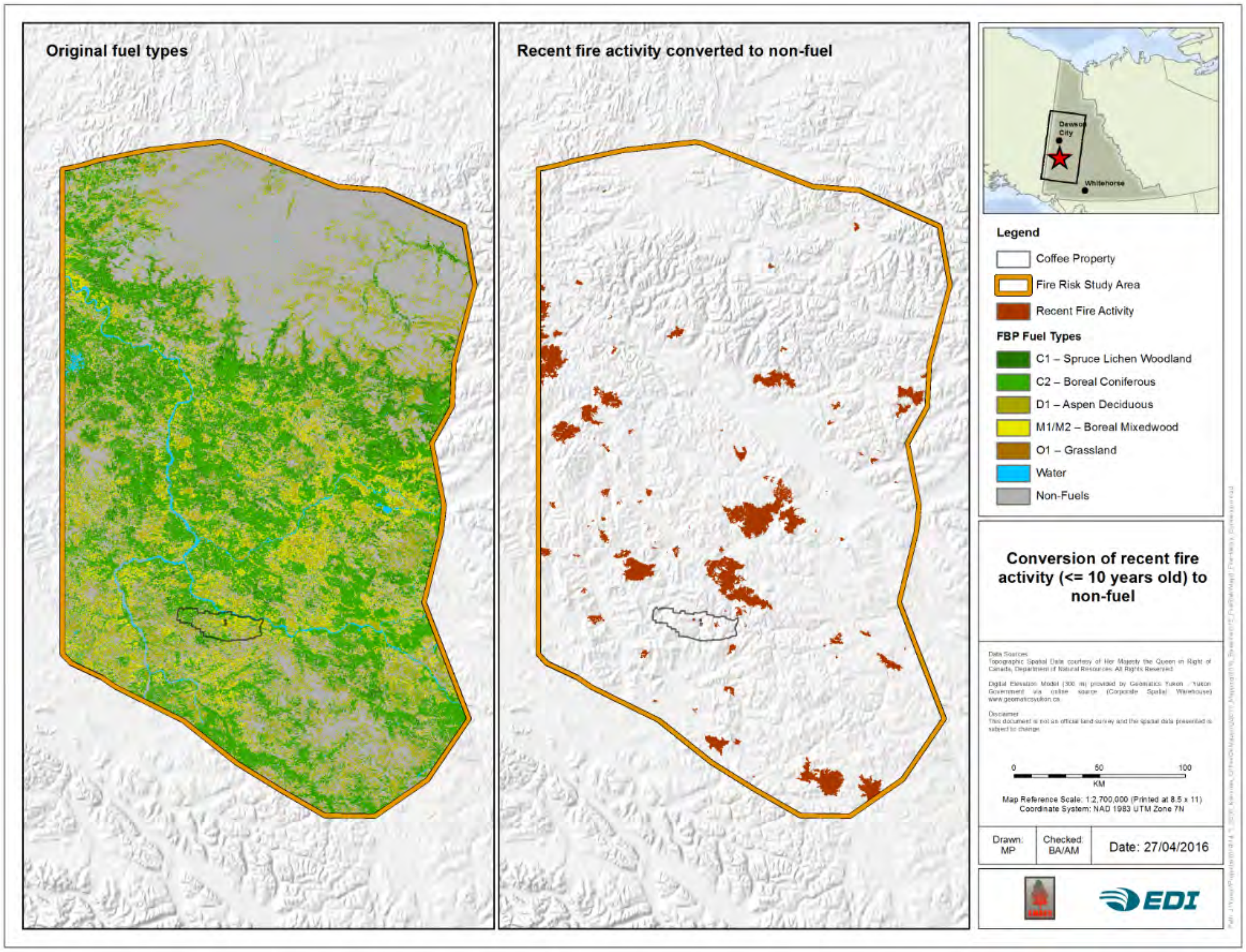


Figure A3.2. Map indicating the areas of recent fire activity (≤ 10 years) re-classified to non-fuel.

APPENDIX 4: BURN-P3 MODEL CALIBRATION

Initial Calibration Attempt **Final Calibration Attempt**

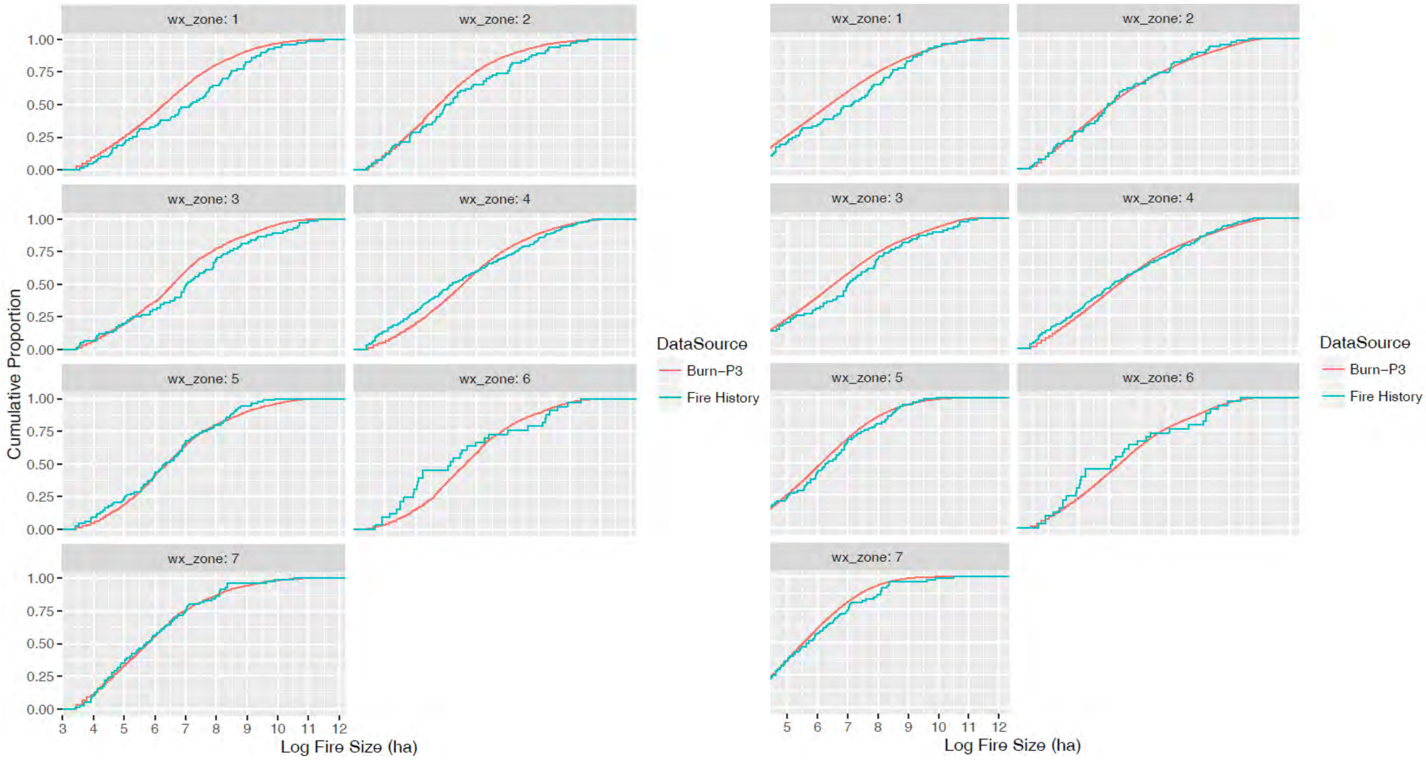


Figure A4.1 Results of the Burn-P3 calibration on the Cumulative Proportion of Log Fire Size (ha) curves by fire/weather zone

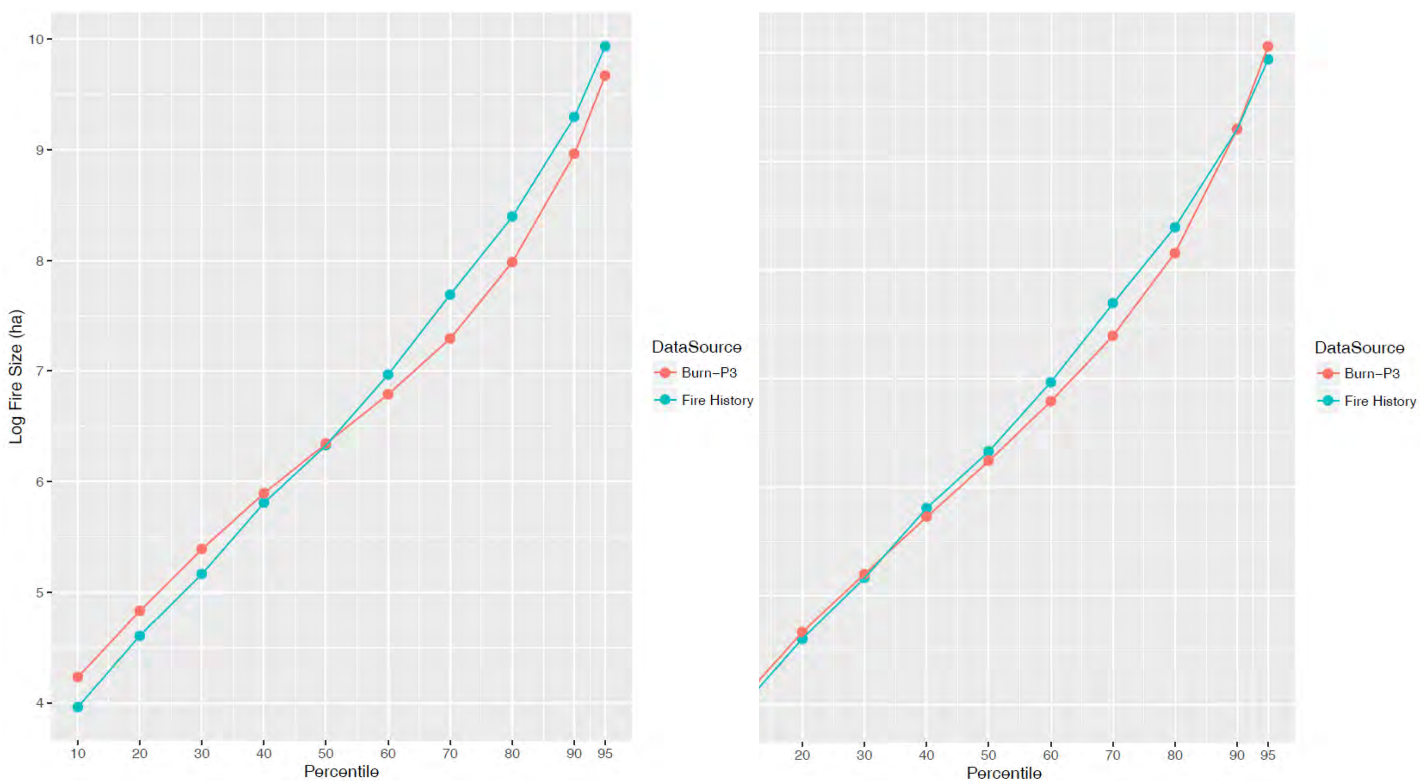


Figure A4.2 Results of the Burn-P3 calibration on the percentile values of Log Fire Size (ha)

Appendix 5: Fire Behavior Prediction (FBP) System Fuel Types

C1 - Spruce–Lichen Woodland

This fuel type is characterized by open, parklike black spruce (Picea mariana (Mill.) B.S.P.) stands occupying well-drained uplands in the subarctic zone of western and northern Canada. Jack pine (Pinus banksiana Lamb.) and white birch (Betula papyrifera Marsh.) are minor associates in the overstory. Forest cover occurs as widely spaced individuals and dense clumps. Tree heights vary considerably, but bole branches (live and dead) uniformly extend to the forest floor and layering development is extensive. Accumulation of woody surface fuel is very light and scattered. Shrub cover is exceedingly sparse. The ground surface is fully exposed to the sun and covered by a nearly continuous mat of reindeer lichens (Cladonia spp.), averaging 3-4 cm in depth above mineral soil.

C2 - Boreal Spruce

This fuel type is characterized by pure, moderately well-stocked black spruce (Picea mariana (Mill.) B.S.P.) stands on lowland (excluding Sphagnum bogs) and upland sites. Tree crowns extend to or near the ground, and dead branches are typically draped with bearded lichens (Usnea spp.). The flaky nature of the bark on the lower portion of stem boles is pronounced. Low to moderate volumes of down woody material are present. Labrador tea (Ledum groenlandicum Oeder) is often the major shrub component. The forest floor is dominated by a carpet of feather mosses and/or ground-dwelling lichens (chieflyCladonia). Sphagnum mosses may occasionally be present, but they are of little hindrance to surface fire spread. A compacted organic layer commonly exceeds a depth of 20–30 cm.

C3 - Mature Jack or Lodgepole Pine

This fuel type is characterized by pure, fully stocked (1000–2000 stems/ha) jack pine (Pinus banksiana Lamb.) or lodgepole pine (Pinus contorta Dougl. ex Loud.) stands that have matured at least to the stage of complete crown closure. The base of live crown is well above the ground. Dead surface fuels are light and scattered. Ground cover is feather moss (Pleurozium schreberi) over a moderately deep (approximately 10 cm), compacted organic layer. A sparse conifer understory may be present.

C4 - Immature Jack or Lodgepole Pine

This fuel type is characterized by pure, dense jack pine (Pinus banksiana Lamb.) or lodgepole pine (Pinus contorta Dougl. ex Loud.) stands (10,000–30,000 stems/ha) in which natural thinning mortality results in a large quantity of standing dead stems and dead downed woody fuel. Vertical and horizontal fuel continuity is characteristic of this fuel type. Surface fuel loadings are greater than in fuel type C3, and organic layers are shallower and less compact. Ground cover is mainly needle litter suspended within a low shrub layer (Vaccinium spp.).

C7 - Ponderosa Pine–Douglas-Fir

This fuel type is characterized by uneven-aged stands of ponderosa pine (Pinus ponderosa Laws.) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) in various proportions. Western larch (Larix occidentalis Nutt.) and lodgepole pine (Pinus contorta Dougl. ex Loud.) may be significant stand components on some sites and at some elevations. Stands are open, with occasional clumpy thickets of multi-aged Douglas-fir and/or larch as a discontinuous understory. Canopy closure is less than 50% overall, although thickets are closed and often dense. Woody surface fuel accumulations are light and scattered. Except within Douglas-fir thickets, the forest floor is dominated by perennial grasses, herbs, and scattered shrubs. Within tree thickets, needle litter is the predominant surface fuel. Duff layers are nonexistent to shallow (<3 cm).

D1 - Leafless Aspen

This fuel type is characterized by pure, semimature trembling aspen (Populus tremuloides Michx.) stands before bud break in the spring or following leaf fall and curing of the lesser vegetation in the autumn. A conifer understory is noticeably absent, but a well-developed medium to tall shrub layer is typically present. Dead and down roundwood fuels are a minor component of the fuel complex. The principal fire-carrying surface fuel consists chiefly of deciduous leaf litter and cured herbaceous material that is directly exposed to wind and solar radiation. In the spring the duff mantle (F and H horizons) seldom contributes to the available combustion fuel because of its high moisture content.

	**O1 - Grass** This fuel type is characterized by continuous grass cover, with no more than occasional trees or shrub clumps that do not appreciably affect fire behavior. Two subtype designations are available for grasslands; one for the matted grass condition common after snowmelt or in the spring (O1-a) and the other for standing dead grass common in late summer to early fall (O1-b). The proportion of cured or dead material in grasslands has a pronounced effect on fire spread there and must be estimated with care. ***Source:*** ***http://cwfis.cfs.nrcan.gc.ca/background/fueltypes/o1***
	**M1 - Boreal Mixedwood–Leafless** This fuel type (and its "green" counterpart, M2) is characterized by stand mixtures consisting of the following coniferous and deciduous tree species in varying proportions: black spruce (Picea mariana (Mill.) B.S.P.), white spruce (Picea glauca(Moench) Voss), balsam fir (Abies balsamea (L.) Mill.), subalpine fir (Abies lasiocarpa (Hook.) Nutt.), trembling aspen (Populus tremuloides Michx.), and white birch (Betula papyriferaMarsh.). On any specific site, individual species can be present or absent from the mixture. In addition to the diversity in species composition, stands exhibit wide variability in structure and development, but are generally confined to moderately well-drained upland sites. M1, the first phase of seasonal variation in flammability, occurs during the spring and fall. The rate of spread is weighted according to the proportion (expressed as a percentage) of softwood and hardwood components.

Source: http://cwfis.cfs.nrcan.gc.ca/background/fueltypes/m4

APPENDIX 6: DESCRIPTION OF FIRE BEHAVIOR POTENTIAL AND IMPLICATIONS FOR WILDFIRE SUPPRESSION IN THE C2 FUEL TYPE BY FIRE INTENSITY CLASS

Interpretations associated with the head fire intensity class graph for Canadian Forest Fire Behavior Prediction (FBP) System Fuel Type C-2 (Boreal Spruce) on level to gently undulating terrain and 85% foliar moisture content.

Fire Intensity Class	Description of Probable Fire Potential and Implications for Wildfire Suppression
1	New fire starts are unlikely to sustain themselves due to moist surface fuel conditions. However, new ignitions may still take place from lightning strikes or near large and prolonged heat sources (e.g., camp fires, windrowed slash piles) but the resulting fires generally do not spread much beyond their point of origin and if they do, control is very easily achieved. Mop-up or complete extinguishment of fires that are already burning may still be required provided there is sufficient fuel and it is dry enough to support smouldering combustion*. Color code is GREEN. [< 10 k W/m]
2	From the standpoint of moisture content, surface fuels are considered sufficiently receptive to sustain ignition and combustion from both flaming and glowing firebrands. Fire activity is limited to creeping or gentle surface burning with maximum flame heights of less than 1.3 m (= 4ft.). Control of these fires is fairly easy but can become troublesome as adverse fire impacts can still result, and fires can become costly to suppress if not attended to immediately. Direct manual attack by "hotspotting " around the entire fire perimeter by firefighters with only hand tools and water from backpack pumps is possible; a "light" helicopter (s) with bucket is also very effective. Fireguard constructed with hand tools should hold. Color code is BLUE. [10 - 500 k W/m]
3	Both moderately and highly vigorous surface fires with flames up to just over 1.5m (= 5ft.) high or intermittent crowning (i.e., torching) can occur. As a result, fires can be moderately difficult to control. Hand-constructed fire guards are likely to be challenged and the opportunity to "hotspot" the perimeter gradually diminishes. Water under pressure (e.g., fire pumps with hose lays) and heavy machinery (e.g., bulldozer, "intermediate" helicopter with a bucket) are generally required for effective action at the fire's head. Color code is YELLOW. [500 - 2000 k W/m]
4	Burning conditions have become critical as intermittent crowning and short-range spotting is common place and as a result control is very difficult. Direct attack on the head of a fire by ground forces is feasible for only the first few minutes after ignition has occurred. Otherwise, any attempt to attack the fire's head should be limited to "medium" or "heavy" helicopters with buckets or fixed-wing aircraft, preferably dropping long-term chemical fire retardants; control efforts may fail. Until the fire weather severity abates, resulting in the subsidence of a fire run, the uncertainty of successful control exists. Color code is ORANGE. [2000 - 4000 k W/m]
5	Intermittent crown fires are prevalent and continuous crowning is also possible as well in the lower end of the spectrum. Control is extremely difficult and all efforts at direct control are likely to fail. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution. Otherwise, any suppression action must be restricted to the flanks and back of the fire. Indirect attack with aerial ignition (i.e., helitorch and/or A.I.D. dispenser), if available, may be effective depending on the fire's forward rate of advance. [> 4000 k W/m] The situation should be considered as "explosive" or super critical in the upper portion of the class. The characteristics commonly associated with extreme fire behavior (e.g., rapid spread rates, continuous crown fire development, medium-to long-range spotting, firewhirls, massive convections columns, great walls of flame) is a certainty. Fires present serious control problems as they are virtually impossible to contain until burning conditions ameliorate. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution; an escaped fire should in most cases, be considered a very real possibility. The only effective and safe control action that can be taken until the fire run expires is at the back and up along the flanks. Color code is RED. [> 10 000 k W/m]

THE ABOVE **SHOULD NOT** BE USED AS A GUIDE TO FIREFIGHTER SAFETY AS WILDLAND FIRES CAN BE POTENTIALLY DANGEROUS OR LIFE THREATENING AT ANY LEVEL OF FIRE INTENSITY.

Source: Alexander, M.E. and F.V. Cole. 1995

Cole, F.V.; Alexander, M.E. 1995. Head fire intensity class graph for FBP System Fuel Type C-2 (Boreal Spruce). Alaska Department of Natural Resources, Division of Forestry, Fairbanks, AK and Natural Resources Canada, Canadian Forest Service, Edmonton, AB. Poster with text.

APPENDIX 7 : CANADIAN FBP SYSTEM FUEL TYPE MAP

The following documentation from the Canadian Forest Service describes the Yukon specific modifications to the Canadian FBP System fuel type database

Source : ftp://ftp.nofc.cfs.nrcan.gc.ca/downloads/Simpson/Fuels Documentation.docx

Yukon/NWT (Yukon.R)
R script location: "W:\EDM\Fire\DeLancey\codes_and_kNN\fuel_code_R"
This script is used in the National product in the ecozones shown below:

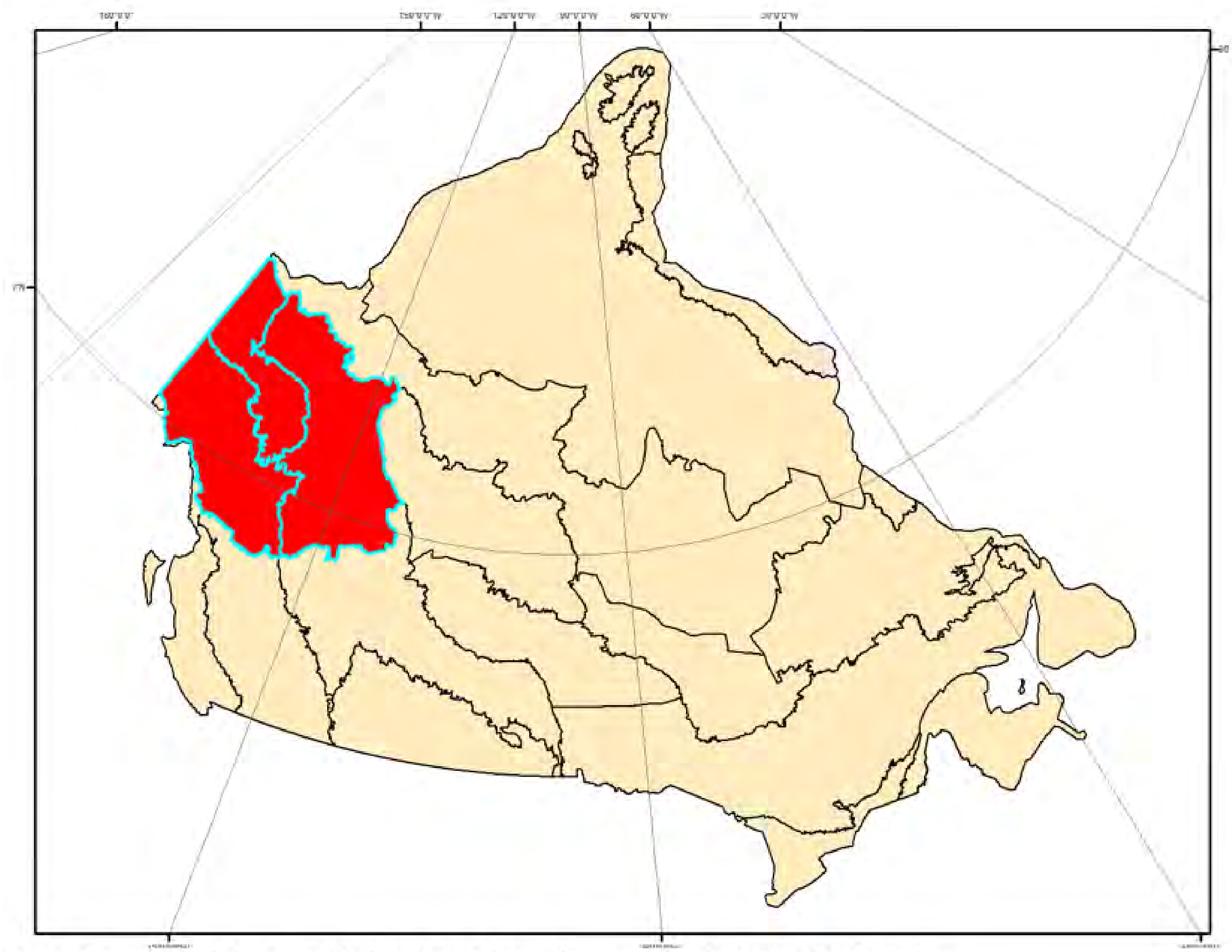


Figure 5: Ecozones labeled in red display where Yukon code was used in the National Fuels product

Script for fuel decision rules:

```
c1=Con(fstack$per_con_int>60&fstack$cc_int<20&fstack$forest_int==1|
fstack$per_con_int>60&fstack$cc_int>=20&fstack$cc_int<=60&fstack$forest_int==1&fstack$ht_int<5,101,0)
c2=Con(fstack$per_con_int>60&fstack$cc_int>=20&fstack$cc_int<=60&fstack$forest_int==1&fstack$ht_int>5,102,0)
c3=Con(fstack$per_con_int>60&fstack$cc_int>60&fstack$forest_int==1&fstack$ht_int>=10&fstack$ht_int<=20|
fstack$pinus_spp>=20&fstack$ht_int>=10|
fstack$per_con_int>=25&fstack$per_con_int<=60&fstack$forest_int==1&fstack$broad_leaf<15,103,0)
c4=Con(fstack$per_con_int>60&fstack$cc_int>60&fstack$forest_int==1&fstack$ht_int<10|
fstack$pinus_spp>=20&fstack$ht_int<10,104,0)
c5=Con(fstack$per_con_int>60&fstack$cc_int>60&fstack$forest_int==1&fstack$ht_int>=20,105,0)
#There is no ponderosa pine in our test study area
c7=Con(fstack$per_con_int>60&fstack$forest_int==1&fstack$pinus_pon>0,107,0)
d1=Con(fstack$per_con_int<25&fstack$forest_int==1|fstack$veg_int>40&fstack$tree_int<20,108,0)
m1=Con(fstack$per_con_int>=25&fstack$unknown<20&fstack$per_con_int<=60&fstack$forest_int==1&fstack$broad
_leaf>15|fstack$ht_int<5&fstack$broad_leaf>10,109,0)
o1=Con(fstack$veg_int>40&fstack$tree_int<20&fstack$tree_int>19.9,116,0)
water=Con(fstack$lc25c2011!=118,1,0)
nonfuel.l=Con(fstack$lc25c2011==119,0,1)
vegnonfuel.l=Con(fstack$lc25c2011==122|fstack$ht_int<4&fstack$tree_int>20,0,1)
urban=Con(fstack$lc25c2011==121,0,1)
```

Changes to code:

- c1=Con(**fstack$per_con_int>60&fstack$cc_int<20**&fstack$forest_int==1| **fstack$per_con_int>60&fstack$cc_int>=20&fstack$cc_int<=60&fstack$forest_int==1&fstack$ht_int<5**,101,0)
    - Reduced crown closure to 20
    - Add in term, if C2 and height less than 5 classify as C1

- c2=Con(fstack$per_con_int>60&**fstack$cc_int>=20**&fstack$cc_int<=60&fstack$forest_int==1&fstack$ht_int>5,102,0)
    - Changes crown closure threshold to match C1

- c3=Con(fstack$per_con_int>60&fstack$cc_int>60&fstack$forest_int==1&fstack$ht_int>=10&fstack$ht_int<=20|fstack$pinus_spp>=20&fstack$ht_int>=10| fstack$per_con_int>=25&fstack$per_con_int<=60&fstack$forest_int==1&fstack$broad_leaf<15,103,0)
    - Classify as C3 if M1, and broad leaf is less than 20, and pinus_spp>20
        - This was done to increase the amount of C3 in the region as it is know that there is not too much M1

- d1=Con(fstack$per_con_int<25&fstack$forest_int==1|**fstack$veg_int>40&fstack$tree_int<20**,108,0)
    - reclassified all O1 as D1

- m1=Con(fstack$per_con_int>=25&fstack$unknown<20&fstack$per_con_int<=60&fstack$forest_int==1&**fstack$broad_leaf>15**|**fstack$ht_int<5&fstack$broad_leaf>10**,109,0)
    - Add in term “broad leaf > 15 and >10” to match C3 reclassify

- o1=Con(fstack$veg_int>40&**fstack$tree_int<20&fstack$tree_int>19.9**,116,0)
    - Essentially remove o1 class but left term in case we want to include it in future versions

- vegnonfuel.l=Con(fstack$lc25c2011==122|**fstack$ht_int<4&fstack$tree_int>20**,0,1)
    - classified as non-fuels if the area was treed(“tree_int>20”) and height was less than 4m