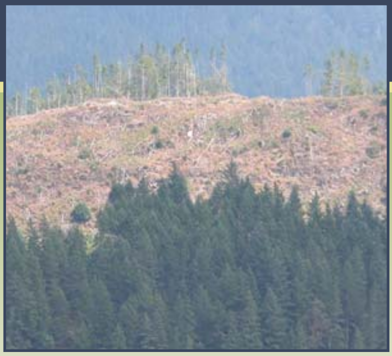
Landscape Projections on Boreal Caribou Habitat in NWT

Summary Report



March 31, 2016

CASLYS CONSULTING

Projected Impacts of Fire and Anthropogenic Disturbance on Boreal Caribou Range in the Dehcho-South Slave Region of NWT

Summary Report

Submitted to:

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March 2016

Acknowledgements

Funding for the project was received from the Government of Canada's National Conservation Plan and NWT Cumulative Impact Monitoring Program (NWT CIMP).

This project was undertaken with the financial support of the Government of Canada.
Ce projet a été réalisé avec l'appui financier du gouvernement du Canada.

The authors would like to acknowledge the following people for their contributions to this project:

- Lisa Smith and James Hodson with the GNWT Environment and Natural Resources Department (GNWT-ENR) for their feedback and guidance throughout this project;
- Kathleen Groenewegen and Matt Quayle with GNWT-ENR for providing data and GIS support;
- Suzanne Lavoie and Brian Calder with Ember Research Services Ltd for their expertise and technical support in developing of the Burn-P3 models; and,
- Robin Kite, Justin McPherson and Jason Shaw of Caslys Consulting Ltd. for assisting with project coordination, data analysis and report compilation.

Suggested Citation

Blyth, C.A., D. Daust, B. Armitage, D. Cichowski, S. Alexander and K. Price. 2016. Landscape projections on boreal caribou habitat in NWT. Prepared for Government of Northwest Territories, Yellowknife, NWT.

Project Team

- Ann Blyth coordinated the project, compiled and edited the document and contributed to various sections.
- Dave Daust developed landscape simulation models and projected and assessed impacts to caribou range.
- Brad Armitage prepared and ran BurnP3 simulations and described burn probability for selected climate projections.
- Deb Cichowskiprepare background sections on caribou habitat and seismic line recovery and assessed the implications of landscape projections for caribou.
- Sharyn Alexander compiled maps, prepared maps for use in simulations, edited the document and prepared figures for the report.
- Karen Price prepared the climate change section, and assisted in interpretation of landscape simulation results.

EXECUTIVE SUMMARY

Overview

To meet federal Recovery Strategy objectives, the Government of the Northwest Territories, Environment and Natural Resources Department (GNWT-ENR) is developing a set of regional plans to demonstrate how habitat conservation targets can be met across the boreal caribou range in the Northwest Territories (NWT). Toward the goal of developing a sustainable timber management plan that meets the objectives of the Boreal Caribou Recovery Strategy, GNWT-ENR sponsored this project to assess the combined impact of forest fires and timber harvesting on boreal caribou habitat under different climate change scenarios.

The Boreal Caribou Recovery Strategy identifies critical habitat as 65% of the boreal caribou range being in an undisturbed condition. At a level of 65% undisturbed range, the boreal caribou population has a 60% probability of being self-sustaining. Higher levels of undisturbed range will result in a higher probability of maintaining a self-sustaining population (Environment Canada, 2012). The study area for the project covers the southern portion of the boreal caribou range in the NWT, which overlaps the Dehcho and South Slave administrative regions. The current undisturbed boreal caribou range within the NWT is 66% (J. Hodson personal communication), and the results of this project indicate 52% of the southern portion of the range within the study area is currently (as of 2015) undisturbed.

The project included four main components:

1) acquiring and consolidating available datasets;
2) developing Burn-P3 (probability, prediction, planning) models to estimate burn probability under various scenarios;
3) developing a landscape model to project future fires and forest harvesting disturbances and recovery over time; and
4) interpreting results from the landscape disturbance/recovery projections with respect to boreal caribou range and forest harvesting.

By modelling the combined impact of forest fires and timber harvesting under different climate change scenarios, the amount, and spatial configuration, of undisturbed habitat for boreal caribou is predicted for current day conditions and into the future.

The results of the Burn-P3 burn probability models were integrated within a Spatially Explicit Landscape Event Simulator (SELES) model to examine landscape recovery and disturbance over time for each of two climate change scenarios: Canadian Centre for Climate Modelling and Analysis (CGCM3.1); and Hadley Centre for Climate Prediction (HadCM3). The HadCM3 model projects hotter and relatively dry conditions into the future. In contrast, the CGCM3.1 model also predicts hotter temperatures but with relatively high precipitation levels. For comparative purposes, simulations were conducted using both models. Different forest harvest and fire scenarios were evaluated to quantify potential impacts on available undisturbed boreal caribou range and timber supply. In particular, we examined potential interactions and feedback between timber harvesting policy, fire disturbance and caribou range disturbance constraints over time.

Burn-P3 Analysis

The following burn probability scenarios were generated for the study area:

- A baseline using the best information currently available to represent conditions in 2015 (Baseline 2015).

- A second baseline using data derived from the modelled results was also generated to facilitate the comparison of relative change between the climate change scenarios over time.
- Four different climate change scenarios:
    - CGCM3.1 covering the time period 2031-2060;
    - CGCM3.1 covering the time period 2061-2090;
    - HadCM3 covering the time period 2031-2060; and
    - HadCM3 covering the time period 2061-2090.

The parameters used in each of the various Burn-P3 scenarios include: fuel type; elevation, weather zones, fire spread event days; escaped fire distribution; and ignition sources and locations.

The results of the Burn-P3 analysis indicate the Baseline (2015) burn probability ranges from a minimum of 0% (non-fuel) to a maximum of 3.76%, with a mean probability for the entire study area of 0.59% (Figure E-1). It was found that only 1% of the study area had a burn probability greater than 2.78%. The results also show the presence of distinct 'hot spots' of higher burn probability. A visual analysis of the burn probability map indicates that many of these hot spots are well correlated with the areas classified as grass (O-1) fuel type, which most closely resembles the shrub cover layer used in similar land cover classifications.

The mean burn probability over the entire study area landscape for all climate change scenarios ranges between 0.76% (CGCM3.1 2080) and 1.05% (HadCM3 2080). The 99th percentile burn probability ranged from 2.42% to 3.21%. When compared against the modelled baseline, the results derived from the hotter and wetter CGCM3.1 model indicate relatively stable burn probability levels over time, with both mean and maximum burn probability being similar throughout the time periods. The results derived from the hotter and drier HadCM3 model indicate an increase in both mean and maximum burn probability into the future. In terms of fire size, the results indicate a general trend toward larger fires into the future.

Landscape Models

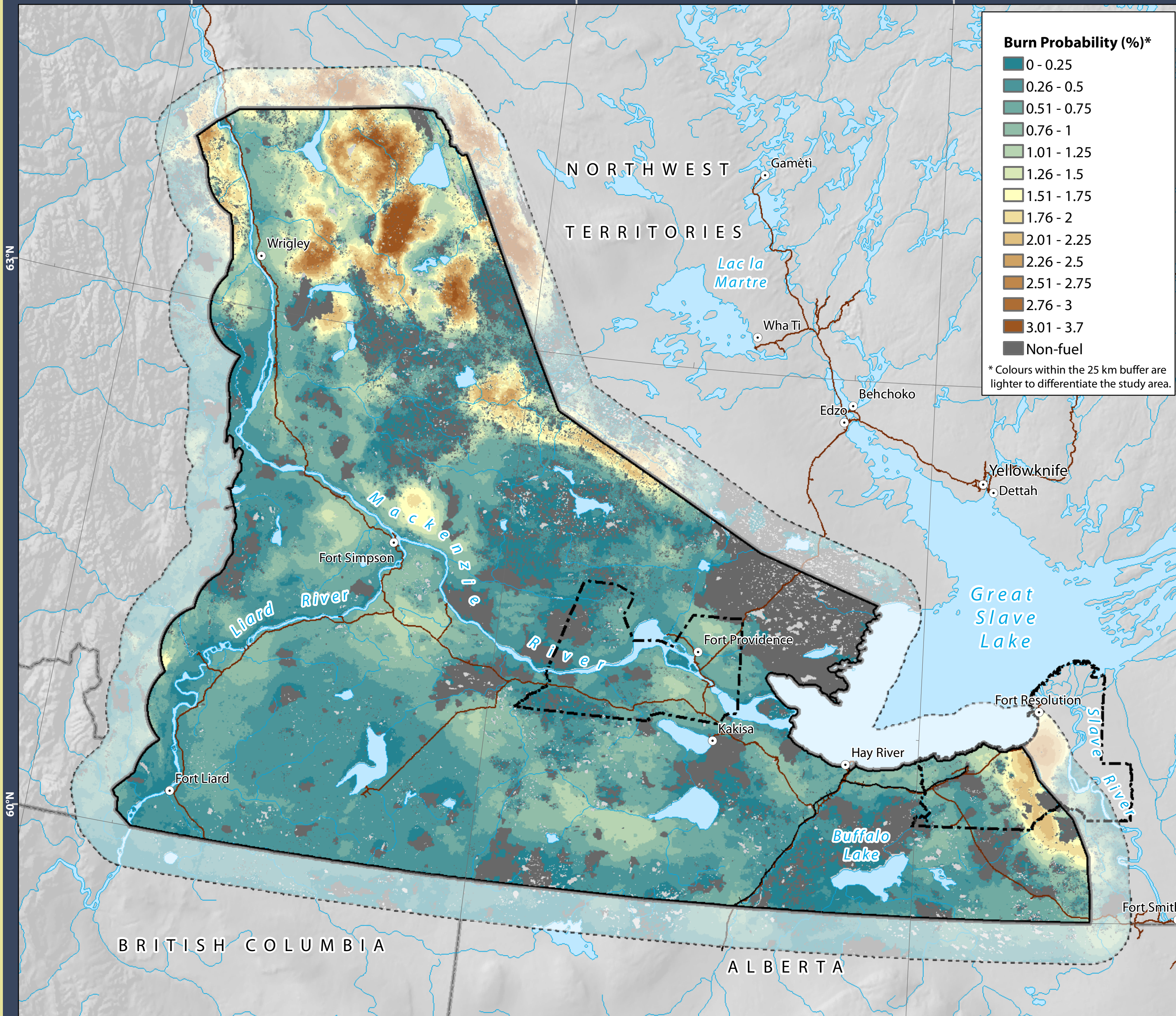
The caribou range landscape disturbance model examines the interaction of fire and anthropogenic disturbance, recovery and climate change. It reports statistics related to the following variables over a 100-year simulation period: undisturbed caribou range; patch size distribution; area harvested; and road construction. The model consists of six main modules:

1) a fire module to simulate the ignition and spread of fires each year;
2) a vegetation and fuel recovery module to simulate changes in fuel types;
3) a future road network module to predefine a realistic road network for areas to be developed for timber harvesting;
4) a timber harvesting module to simulate the size and location of cutblocks for each time period;
5) a seismic line recovery module to simulate the recovery of seismic lines; and
6) caribou range statistics module to identify patches of undisturbed range bounded by disturbed range and calculate the area in each patch-size class.

Simulation experiments were run to examine potential future outcomes for boreal caribou range and timber supply using different plausible assumptions related to fire disturbance and fuel recovery, climate change, timber harvesting and vegetation recovery conditions. The behaviour and effects of each of the main factors that disturb caribou habitat were examined: existing linear and areal features; future timber harvest and related road development; and fire disturbance. In addition, the cumulative effects of these factors acting in combination on caribou range and on timber harvest are quantified.

Figure E-1

Actual Baseline (2015) Scenario Burn Probability



Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

Many existing anthropogenic features (e.g., settlement, mines, gas wells, roads, powerlines) are considered to be relatively permanent and thus create a stable disturbance footprint over the simulation period. Permanent areal features cover a very small portion of the study area (about 0.1%). Permanent linear features also have a relatively small footprint, even when buffered by 500 metres either side (2-3% of the study area). The existing approximately 25,000 km of seismic lines represent the largest anthropogenic disturbance footprint (about 12% of the study area), however seismic lines have the potential to recover their habitat value over time. At the present time (2015), accounting for the overlap of fires and anthropogenic features, 52% of the range within the study area is undisturbed (Figure E-2).

Within the study area, most existing seismic lines (about 80%) are expected to recover within 50 years, reducing range disturbance by roughly 10% over this period. Remaining seismic lines are projected to recover more slowly. Connectivity among patches of undisturbed range improves substantially over the next 25 years as sections of seismic lines recover. Consequently, the proportion of range in patches greater than 500 km^2 also increases, although small breaks in the linear disturbance may not reduce overall predation risk associated with the longer, unrecovered portions of the linear features.

The Fort Providence and Fort Resolution Forest Management Areas (FMAs) represent 7.1% of the study area. However, only approximately 1% of the study area is currently available for forest harvesting as only a portion of the two FMAs are merchantable timber. Therefore, the contribution of forest harvesting to range disturbance over the entire study area is relatively low, increasing disturbed range by about 2% over the next 100 years. Expansion of forestry activities within the entire study area would however cause more substantial disturbance, as forest harvesting creates high levels of disturbance per unit area. Fire is the dominant disturbance on the landscape, covering 38% of the study area (including 7% burned in the five years since 2011), and is currently the main cause of disturbance to the boreal caribou range (Figure E-2).

A series of scenarios were run to explore the effects of timber harvest and fire disturbance on undisturbed range abundance within a cumulative-effects simulation model that includes climate change, fire, fuel recovery and succession, timber harvest, existing linear and areal disturbance and habitat recovery (from fire, timber harvest and seismic lines). Twelve scenarios examined the effects of different combinations of timber harvesting, climate change and fuel succession assumptions, each with 10 replicates (for a total of 120 simulations) to characterize variability within the scenario. The results, depicted in Figure E-3, show the current undisturbed range within the study area (52%) increasing over the next 100 years. A substantial increase occurs between year zero and 25, due to recovery of seismic lines and historical fires, with a smaller increase between years 75 and 100.

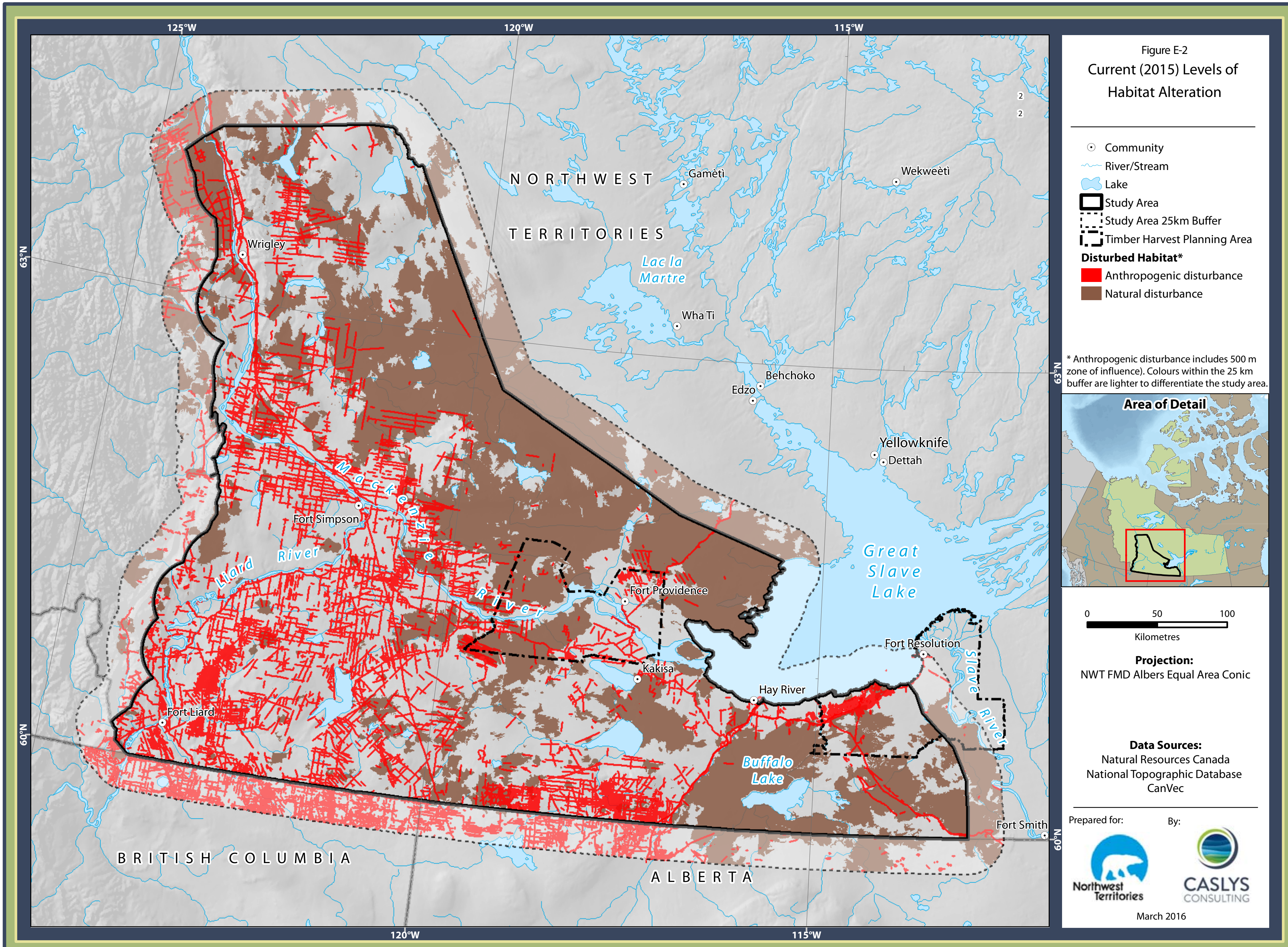
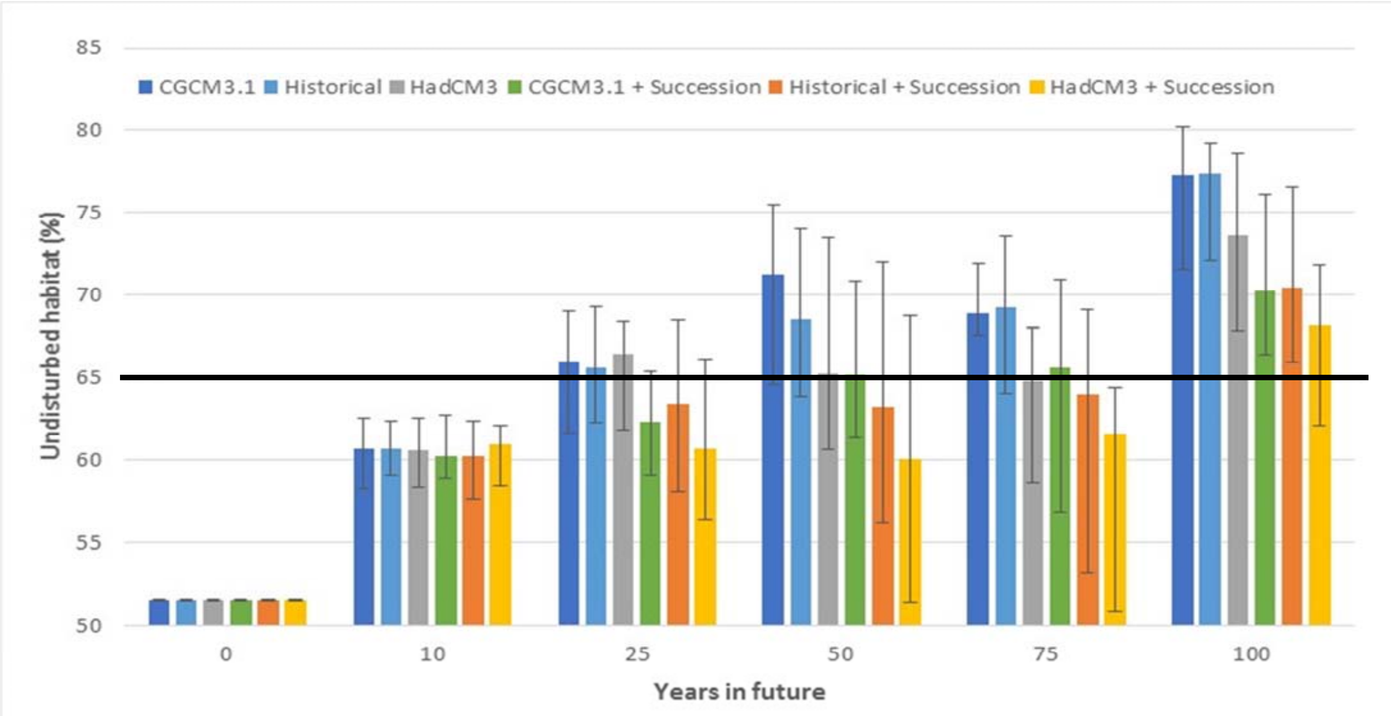


Figure E-2
Current (2015) Levels of Habitat Alteration

Figure E-3. Median Undisturbed Range Resulting from Different Fire Scenarios (Year 0 = 2015)*; Timber Harvest and No Timber Harvest Scenario Results are Combined



Timber harvest and no-timber harvest results are combined for each sample year. Whiskers bracket the middle 50% of results. The black line highlights the 65% undisturbed habitat target.

Additional factors impact the undisturbed range calculations, including regeneration delay and type of disturbance. The Recovery Strategy used 40 years for recovery of boreal caribou range following fire. However, ecological recovery and growth rates are very slow in the NWT, and forests experience a regeneration delay of up to 50 years. This could present overly optimistic undisturbed range calculations if regeneration delay is not taken into account. In addition, the Recovery Strategy combined anthropogenic and natural disturbances to examine overall impacts over a vast area. Assuming natural disturbances have a lower risk to caribou, the primarily fire-disturbed habitat in the NWT may reduce functional habitat less than anthropogenic disturbances.

Undisturbed patches >500 km^2 currently comprise 83% of the undisturbed area, and it was found that the area of these large patches increased over time. This increase was primarily due to recovery of portions of seismic lines together with the assumption of no new seismic lines. Undisturbed patch size could potentially jump substantially when two polygons are connected after a small portion of a seismic line achieved recovery. When assessing undisturbed range following recovery of disturbed habitat, especially in cases where only portions of seismic lines recover, a combination of patch size and patch shape may provide a better representation of functionally undisturbed range than patch size alone.

Data Limitations and Uncertainty

The following limitations are associated with the source data and results of this project:

- The model did not examine increased forest harvesting activity, exploration, seismic activity, settlement, or additional anthropogenic disturbance over time;

- The simulations did not fully explore different assumptions about baseline historical burn rates;
- The influence of vegetation recovery and succession on fuel flammability would benefit from better understanding and calibration;
- The existing fire data do not identify unburned or partially-burned patches within the fire perimeter; and
- The NWT forest inventory is insufficient to assess stand age and land cover reliably within the study area.

In addition, it should be understood that predicting fire disturbance is difficult given the limited knowledge about the fire regime and stochastic variability in fire location and weather patterns. Uncertainty with regard to baseline annual burn rates, future climate conditions, and recovery of fuel flammability following disturbance were all examined:

- Estimates of mean area burned annually due to the historical fire regime vary from approximately 0.6 to 1.2%/year by region. As a baseline, the fire model was calibrated to burn about 0.9%/year on the 2011 landscape, an amount lying within the range suggested by historical data and the Burn-P3 model results. Hence, uncertainty around the estimated historical mean annual burn rate is +/- 33%.
- Area burned was estimated using climate projections and historical weather data. Climate models vary substantially in their predictions of summer temperature and precipitation, and consequently in their predictions of area burned: the wetter CGCM3.1 model leads to decreased annual burn, while the hotter and drier HadCM3 model increases burn rate over time. Modelled burn area is influenced by uncertainty in both fire and climate models, and ranges from -11% to +24% by 2080.
- Fuel recovery assumptions also influence fire behaviour, and hence annual burn rate. Following disturbance, stands have a higher chance of recolonizing with less-flammable deciduous species; over time, the deciduous component declines and the more flammable conifer component increases. Together, assumptions about recovery rate and succession account for +/- 10% uncertainty.

Based on the ranges of uncertainty associated with each of these issues, the cumulative level of uncertainty ranges from -54% to +67% of the modelled midpoint. This variation leads to a change in boreal caribou range of approximately +/- 15%.

Next Steps

Future studies could provide additional information to support decision-making related to boreal caribou, including:

- Explore the potential to apply minimum undisturbed-range targets that vary among subregions within NWT boreal caribou range.
- Estimate future disturbance in other subregions of NWT boreal caribou range to support range-wide planning.
- Develop a long-term research/monitoring strategy to examine the effects of fire and anthropogenic disturbance on boreal caribou population dynamics.
- Develop a research/monitoring program to examine ecosystem recovery following fire and anthropogenic disturbance.
- Work with climate researchers to establish a long-term weather monitoring network across boreal caribou range.
- Develop a land cover map that would allow a more up-to-date fuels layer to be derived.

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1.0 INTRODUCTION

The *Recovery Strategy for the Woodland Caribou (Rangifer tarandus caribou), Boreal population, in Canada* (Environment Canada, 2012) (hereafter referred to as the Recovery Strategy) identifies critical habitat for boreal caribou as a minimum of 65% of a boreal caribou range in an undisturbed condition. In addition, Nagy (2011) suggests that large patches of undisturbed range are required to maintain viable populations of boreal caribou.

In the Northwest Territories (NWT), all boreal caribou fall within one range, which is currently 66% undisturbed (J. Hodson personal communication). The southern portion of the range has experienced greater levels of disturbance and habitat alteration than other regions to the north. Fire is the primary disturbance factor on the boreal caribou range, but historical oil and gas exploration activities have left a legacy of linear features on the landscape, and forest harvesting is expected to contribute to habitat disturbance over the next 25 years as the Government of the NWT (GNWT) recently entered into Forest Management Agreements (FMAs) with aboriginal companies in the southern portion of the range.

To address critical habitat identified in the Recovery Strategy, GNWT Environment and Natural Resources Department (GNWT-ENR) is developing regional plans within the boreal caribou range. Due to the higher levels of disturbance in the southern portion of the range, the priority is on developing regional range plans for the Dehcho and South Slave administrative regions.

The purpose of this project is to model the combined impact of forest fires and timber harvesting under different climate scenarios to predict the amount and spatial configuration of undisturbed range for boreal caribou. This information will provide decision support to the regional planning processes.

Specific objectives of the project are to:

- identify areas susceptible to near-term fires (i.e., 25 years) to facilitate short-term decisions regarding timber harvest, fire management, and the protection of undisturbed areas for boreal caribou range;
- project and assess the amount and patch-size distribution of undisturbed boreal caribou range using various scenarios of future fire frequency, severity, annual burn, and timber harvest to evaluate the implications to undisturbed range for boreal caribou at different future time scales (e.g., 25, 50 and 100 years);
- evaluate the potential impact of future fire and commercial timber harvest scenarios on boreal caribou range targets, which include maintaining at least 65% undisturbed range, roughly half of which should be in patches greater than 500 km^2 in size;
- assess the influence of human land use activities on the future natural and human disturbance footprint, particularly the rate and method of transition of linear features back to undisturbed habitat under different future time scales (e.g., 25 years for upland habitat features, 50 years for lowland habitat features); and,
- evaluate the use of timber harvesting to manage fire risk and spread, toward the goal of maintaining boreal caribou range[1].

[1] The results of our analyses indicated that there was no detectable effect of timber harvest on fire risk and spread. This is probably due to the relatively small area under consideration for timber harvest relative to the entire study area. As a result, the use of timber harvest to manage fire risk and spread was not examined in detail.

1.1 Overview

The project included four main components: 1) acquiring and consolidating available data layers; 2) developing Burn-P3 (probability, prediction, planning) models to estimate burn probability under various scenarios; 3) developing a landscape model to project future fires and forest harvesting disturbances and recovery; and, 4) interpreting results from the landscape disturbance/recovery projections with respect to boreal caribou range and forest harvesting.

The Burn-P3 model (Parisien et al., 2005) used similar methods as those applied in a recent Burn P3 assessment of the southern half of the study area to ensure continuity. The results of the burn models were integrated within a Spatially Explicit Landscape Event Simulator (SELES) model (Fall and Fall, 2001) to examine landscape recovery and disturbance over time for each of two climate change scenarios (Canadian Centre for Climate Modelling and Analysis (CGCM3.1), Hadley Centre for Climate Prediction (HadCM3)). Different harvest policies and fire scenarios were evaluated to quantify potential impacts on available undisturbed boreal caribou range and timber supply. In particular, we examined potential interactions and feedback between timber harvesting policy, fire disturbance and caribou range disturbance constraints over time. The resultant models and derivative data products can support development of GNWT-ENR decision-making strategies that better meet their targets for undisturbed range and undisturbed patch size while integrating future timber harvest scenarios.

Both of the modelling packages used for this project (Burn-P3 and SELES) are available in the public domain. The software and more information related to Burn-P3 may be found at http://www.ualberta.ca/~wcwfs/burn-p3-en.html and SELES at http://www.gowlland.ca/downloads/index.html. Source inputs and model parameters for both models are thoroughly documented ensuring that the results: are defensible, can be duplicated, and can be updated easily in the future as additional information becomes available. All spatial datasets are in ArcGIS format, with accompanying metadata, to ensure compliance with GNWT-ENR's standards for GIS data (Appendix A).

The following timber harvesting, fire, and linear/areal feature recovery scenarios were used for this project:

<u>Timber Harvesting Scenario</u>

1. A combined projected annual harvest of 250,000 m^3 within two Forest Management Areas (FMAs): Fort Providence and Fort Resolution. Note that only a portion of the Fort Resolution FMA lies within the study area.

<u>Fire Scenarios</u>

1. A future fire regime similar to the existing fire regime based on fire history for the study area from 1965-2015.
2. Future fire regimes under two different climate change scenarios: Canadian Centre for Climate Modelling and Analysis' third generation GCM (CGCM3.1), and the Hadley Centre for Climate Science and Service's third generation model (HadCM3).

<u>Linear/Area Feature Recovery Scenarios</u>

1. Recovery of seismic lines based on existing literature
2. No change in relatively permanent linear and areal features (e.g., roads, mines, settlement)

Our assessment considered the cumulative effects of these factors acting in combination on caribou range.

1.2 Study Area

The project study area, which overlaps the southern portion of the boreal caribou range in the territory, is located in the southwest region of NWT (Figure 1). It includes the Dehcho and South Slave administrative regions and the communities of Hay River, Fort Simpson and Fort Providence. The Fort Resolution and Fort Providence Timber Harvest Planning (THP) areas support the two FMAs, and cover 7.1% of the study area. The Mackenzie and Liard rivers flow through the area. The eastern tip of Nahanni National Park is located along its western edge and the northwestern corner of Wood Buffalo National Park lies in the southeast. In addition, several proposed protected areas are located within the study area.

The average annual temperature for the majority of the study area is -4.4 to -1.0 °C and annual precipitation ranges from approximately 200 to 400 millimetres (Ecosystem Classification Group, 2009). Falling within the Taiga Plains ecoregion, the majority of the area is dominated by flat, rolling terrain with few significant hill systems. The landscape contains extensive peatlands and boulder till plains in upland areas. Predominant tree species include birch, aspen, alder, pine and spruce. Fires are common in this ecoregion, resulting in patches of forest types at difference stages of succession.

Totalling 158,391 km^2, the study area overlaps with the Great Slave Lake (GSL) and Lake Athabasca (LA) homogenous fire zones and partially overlaps with the Southern Prairies and Interior Cordillera fire zones (Boulanger et al., 2014). A buffer distance of 25 kilometres was applied to the study area to reduce negative implications of edge-effects (e.g., to allow the spread of fires to not be restricted to the study area boundary) on the results within the study area itself. This increased the analysis area by 54,498 km^2, resulting in a total area of 212,889 km^2.

1.3 Background

1.3.1 Boreal Caribou Habitat Requirements

The Recovery Strategy (Environment Canada, 2012) summarized the habitat requirements and biological needs of boreal caribou as follows:

- boreal caribou require large range areas comprised of continuous tracts of undisturbed habitat, which reduce the risk of predation by allowing them to maintain low population densities throughout the range and by allowing them to avoid areas of high predation risk, such as areas with high densities of alternate prey species;
- boreal caribou prefer habitat consisting of mature to old-growth coniferous forests (e.g., Jack pine, black spruce) with abundant lichens, or muskegs and peatlands intermixed with upland or hilly areas. They avoid early seral forests and recently disturbed areas;
- during winter, boreal caribou require habitat that has arboreal lichens and shallower snow (e.g., mature coniferous stands with closed canopies and upland or hilly areas exposed to wind), where it is easier to dig for terrestrial lichens;
- during calving and post-calving, pregnant cows use isolated, relatively predator-free areas where nutritious forage is available, such as islands in lakes, peatlands or muskegs, lakeshores and forests; and,
- boreal caribou use a variety of habitats to avoid predators, including muskegs and bodies of water, and mature and old-growth forests.

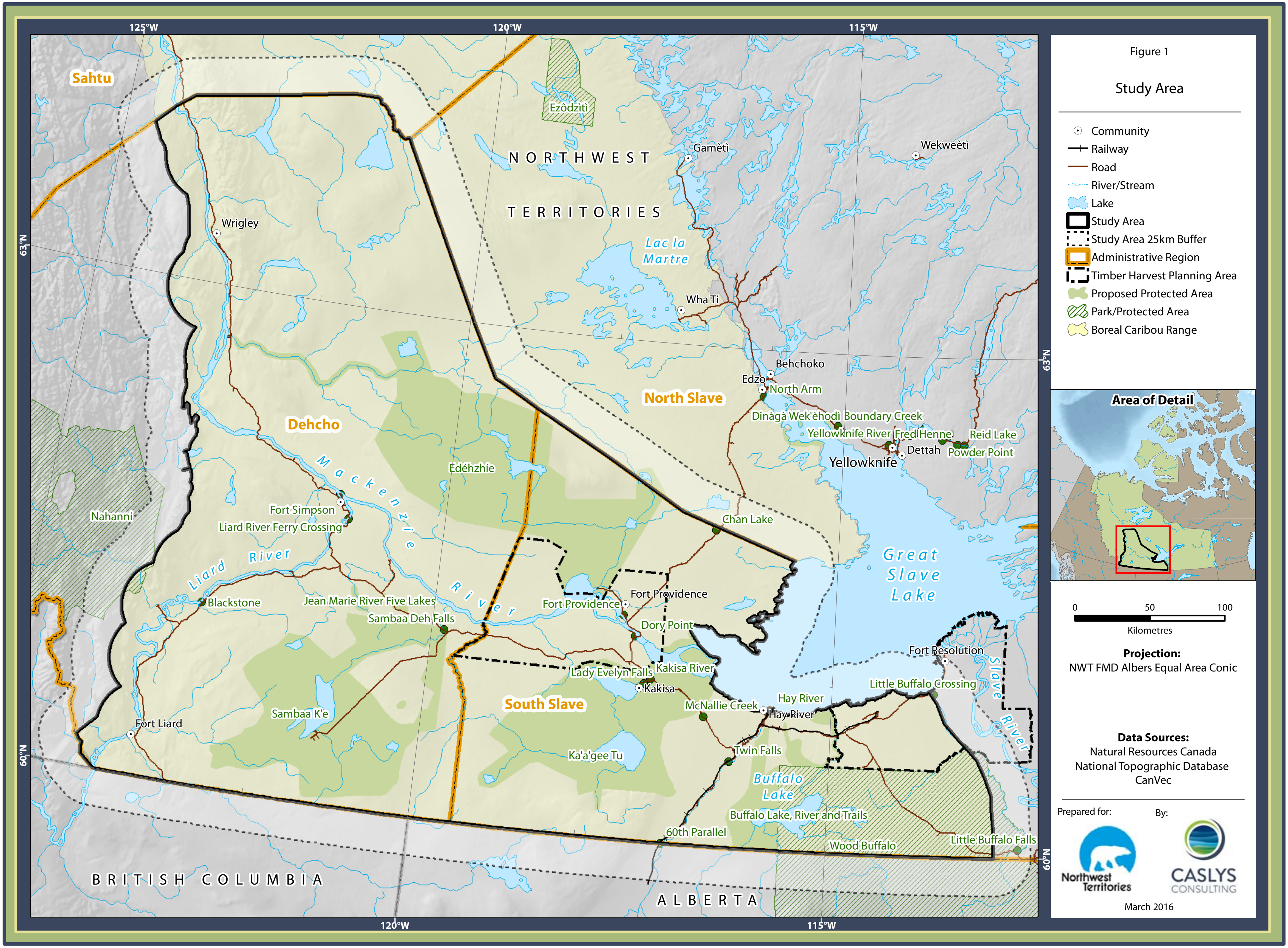


Figure 1

Study Area

Both natural and anthropogenic habitat disturbances affect boreal caribou through changes in vegetation composition, however, linear features associated with anthropogenic habitat disturbance (e.g., roads, seismic lines) also pose additional threats.

The Recovery Strategy (Environment Canada, 2012) identifies critical habitat as:

- the area within the boundary of each boreal caribou range that provides an overall ecological condition that will allow for an ongoing recruitment and retirement cycle of habitat, which maintains a perpetual state of a minimum of 65% of the area as undisturbed habitat; and,
- biophysical attributes required by boreal caribou to carry out life processes.

The Recovery Strategy (Environment Canada, 2012) defines disturbance as i) anthropogenic disturbance visible on Landsat at a scale of 1:50,000 including habitat within a 500 metre buffer of the anthropogenic disturbance, and/or ii) fire disturbance in the last 40 years, as identified in data from each jurisdiction (without buffer).

At a level of 65% undisturbed habitat, a boreal caribou population has a 60% probability of being self-sustaining (Environment Canada, 2011). Nagy (2011) suggests that viable populations of boreal caribou can be maintained in areas with low predator and alternate prey diversity, and where ≥ 46% of the area is secure unburned habitat (i.e., >400 metres from seismic lines) and 54% of that secure unburned habitat is in patches >500 km^2.

Habitat alteration can affect boreal caribou by:

- reducing abundance of terrestrial and arboreal lichens, which are the preferred winter forage of boreal caribou;
- increasing predator density by providing habitat conditions that favour other prey species (e.g., moose and deer);
- facilitating predator movements on linear features (e.g., roads, seismic lines) associated with anthropogenic disturbances, thereby increasing predator hunting efficiency;
- improving access resulting in increased human activities, which could lead to:
    - increased mortalities due to vehicle collisions, hunting or poaching; and,
    - displacement of boreal caribou due to sensory disturbance (requiring increased energy expenditures) into areas with potentially lower forage quality or higher predation risk;
- boreal caribou avoidance of areas that are in close proximity to altered habitat and linear features; and,
- increasing the density of boreal caribou in undisturbed habitat patches, resulting in the erosion of the anti-predator strategy of living at low densities.

The Recovery Strategy (Environment Canada, 2012) identified human-induced habitat alterations that have caused an imbalance in predator-prey relationships resulting in unnaturally high predation rates on boreal caribou as the major factor affecting the viability of most boreal caribou populations.

Recovery of boreal caribou habitat following disturbance depends on the habitat function that is being addressed (Table 1). Preferred caribou forage lichens are slow growing and poor competitors against other vegetation, and generally do not become abundant following disturbance until later stages of succession. A longer timeline is also required for recovery of mature and old-growth forested anti-predator habitats following disturbance. With respect to increased alternate prey habitat and increased predator efficiency due to linear features, boreal caribou habitat recovery is expected to occur in the moderate term when early successional habitats have transitioned beyond the herb/shrub stage (favoured by alternate prey) and when sufficient vegetation growth has resulted in obstructed sight lines and travel corridors on linear features. Similarly, boreal caribou habitat recovery with respect to human activities is expected in the moderate term once sufficient vegetation growth has obstructed travel corridors on linear features, assuming that no effort is made to keep those travel corridors open. Although some predator-prey dynamics issues may be alleviated in the moderate term, Ray (2014) cautions that this "should not distract focus from the need to rapidly re-establish forest vegetation with compositional and structural characteristics of caribou habitat."

Table 1. Anticipated Timeline for Recovery of Boreal Caribou Habitat

Function	Habitat Condition Required by Caribou	Timeline for Recovery
Caribou forage	• Abundant lichens	Long term
Alternate prey habitat	• Alternate prey forage (e.g., moose browse, grass, etc.) present at levels similar to those prior to disturbance	Moderate term
	• Edge habitat (between early seral and later successional stages) present at levels similar to those prior to disturbance	Moderate-Long term
Predator avoidance	• Obstructed sight lines on linear features • Obstructed travel corridors on linear features	Moderate term
	• Functional anti-predator habitats (e.g., undisturbed, unfragmented mature/old growth forests, muskegs, islands in lakes, etc.)	Long term
Human activity avoidance	• Obstructed travel corridors on linear features	Moderate term

1.3.2 Range Disturbance and Recovery

The many seismic lines covering the study area, reflecting a history of mineral, oil and gas exploration, contribute substantially to disturbed habitat. Most of these linear features are recovering over time, however, some small proportion are likely to be maintained in a disturbed state by ongoing motorized access (Lee and Boutin, 2006).

Timber harvest and the roads developed to access harvest blocks reduce the amount of habitat available to boreal caribou. Conversely, boreal caribou conservation measures may limit logging activity.

Fire is the major cause of natural disturbance in the NWT and in the study area (Environment Canada, 2012). Based on recent fire history, roughly 25% of the NWT, 26% of the Dehcho region and 37% of the South Slave region is expected to be stands less than 40 years old (J. Hodson, GNWT, unpublished data). Fires tend to burn uphill and fire disturbance varies based on the flammability of different fuel types. In decreasing order of flammability, fuels include boreal conifer, mixedwood, open grassland, woodland conifer and deciduous trees. Climate change may increase fire hazard by increasing summer drought and lengthening fire seasons. While insects and disease cause less total disturbance than fire, they affect the flammability of fuels in complex ways that vary with disturbance intensity and time since disturbance.

Following disturbance, recolonization, growth and species succession alter the value of a given stand for caribou, for timber and as fuel for fires. In northern boreal forests, recolonization is a dominant force; most stands retain their initial species composition for many decades. Although stem densities may remain roughly constant over time in mixed aspen-spruce stands, fast-growing aspen may appear dominant for several decades until the initially slower growing spruce overtakes it. In southern boreal forests, aspen is replaced by fir and spruce over time (Bergeron and Fenton, 2012). Some studies suggest that the pre-disturbance stand composition is a good predictor of the post disturbance stand composition (Weber and Stocks, 1998). Continued

site dominance by one species may be particularly true for woodland black spruce, which is both well-adapted to the ecosystem and to fire disturbance.
Various metrics have been used to assess the recovery of habitat (specifically vegetation) following disturbance (Table 2). Recovery of anthropogenic features has been examined based on visibility of the feature using 1:50,000 Landsat imagery (Environment Canada, 2012), regeneration of vegetation to 3 metres using LiDAR (van Rensen et al., 2015), and 50% cover of woody vegetation seen on aerial photographs (Lee and Boutin, 2006). For fire, the Recovery Strategy used a time since disturbance value of 40 years.

Table 2. Metrics Used as Indicators of Recovered Habitat

Data Source	Disturbance Type	Recovered Habitat Indicator
Environment Canada (2012)	• anthropogenic	• habitat not showing any anthropogenic disturbance visible on Landsat at a scale of 1:50,000, including habitat within a 500 metre buffer of the anthropogenic disturbance
	• fire	• habitat not showing any fire disturbance in the last 40 years, as identified in data from each provincial and territorial jurisdiction (without buffer)
van Rensen et al. (2015)	• seismic lines	• regeneration to 3 metre (all vegetation) using LiDAR
Lee and Boutin (2006)	• seismic lines	• 50% (39-63%) cover of woody vegetation seen on aerial photographs

Although time-since-disturbance thresholds are simple to employ, they are not always accurate predictors of recovery (Bayne et al., 2011; Ray, 2014; van Rensen et al., 2015). Ray (2014) points out that the recovery relationship is a continuum and is not binary, therefore using a time-since-disturbance threshold may not reflect the variability in recovery response. The type of disturbance also affects recovery time: linear features may take longer to recover than cutblocks (Ray, 2014). Findings from studies examining vegetation recovery on seismic lines include:

- poor or no recovery in wet lowland areas (Seccombe-Hett and Walker-Larsen, 2004; Lee and Boutin, 2006; Bayne et al., 2011, van Rensen et al., 2015; Kansas et al., 2015);
- seismic lines cut in aspen and mixedwood forests were far more likely to have trees than conifer stands or bogs (Bayne et al., 2011);
- after 35 years, about 10% of seismic lines in aspen and white spruce forests had 50% cover of woody vegetation (Lee and Boutin, 2006);
- regeneration was predicted to occur most quickly in the mesic sites with 2-3 metre depth-to-water (van Rensen et al., 2015);
- approximately one-third of existing conventional seismic lines on the landscape are predicted to fail to regenerate to a 3 metre height after 50 years (van Rensen et al., 2015);
- seismic lines further from roads experienced higher rates of regeneration (van Resen et al., 2015); and,
- after 35 years, about 64% of seismic lines had not recovered to 50% cover of woody vegetation, about 21% transitioned into vehicular tracks, about 8% recovered to 50% cover, and about 6% transitioned to gravel/paved roads or other industrial uses (Lee and Boutin, 2006).

The most consistent finding was poor or no recovery in wet lowland areas. No recovery was found in these sites within 35 years (Lee and Boutin, 2006) or within 33-37 years (Seccombe-Hett and Walker-Larsen, 2004), and van Rensen et al. (2015) predicted disturbed fens were unlikely to regenerate to a 3 metre height even after 50 years.

Lee and Boutin (2006) provide relationships from northeastern Alberta that show seismic line recovery to 50% cover of woody vegetation (conifer and deciduous) or conversion to vehicular tracks/roads to 35 years from time since seismic line establishment. Van Rensen et al. (2015) predict the percentage of seismic lines regenerated to 3 metres height in 10, 30 and 50 years following the date of LiDAR collection in 2007.

Terrestrial lichen recovery in boreal forests after fire generally follows a successional gradient (Ahti, 1977; Morneau and Payette, 1989). *Cladonia sp*. (cup lichens) are most abundant about 10 to 30 (up to 50) years following fire. The reindeer lichens *Cladina mitis*, *C. rangiferina*, and *C. arbuscula* become dominant about 30 to 80 (up to 120) years following fire. The reindeer lichen *Cladina stellaris* dominates starting 80 to120 years after fire (Ahti, 1977; Morneau and Payette, 1989), however, this later stage of succession can also be dominated by *Stereocaulon paschale* (Johnson, 1981). In stands with denser canopies, terrestrial lichen cover declines in later stages of succession (Maikawa and Kershaw, 1976; Boudreault et al., 2015).

1.3.3 Fire Ecology in the Study Area

1.3.3.1 Mean Annual Area Burned and Mean Fire Size

Historical area burned (also called fire frequency) can be estimated directly using mapped fires or estimated from forest age data that reflect time since fire (Johnson and Gutsell, 2004). We calculated several rough estimates of annual burn using fire history and forest age data, assuming that fire disturbance follows a simple negative exponential model. The negative exponential model allows burn rate to be calculated from the proportion of area above a given age. Several other calculation approaches were also used (Table 3). Using different types of calculations over a variety of areas helps to bound the estimated burn rate.

Estimates of percentage burned applicable to the study area range from about 0.7 – 1.2%/year (Table 3). The lower estimates for Gwichin, Sahtu and NWT are considered less applicable because Gwichin and Sahtu are located further north, and NWT covers the whole territory. All estimates of return interval and annual burn are based on the full study area, not just the flammable portion.

Table 3. Estimates of Percent Area Burned per Year and of Fire Return Interval in the Study Area and Nearby Regions

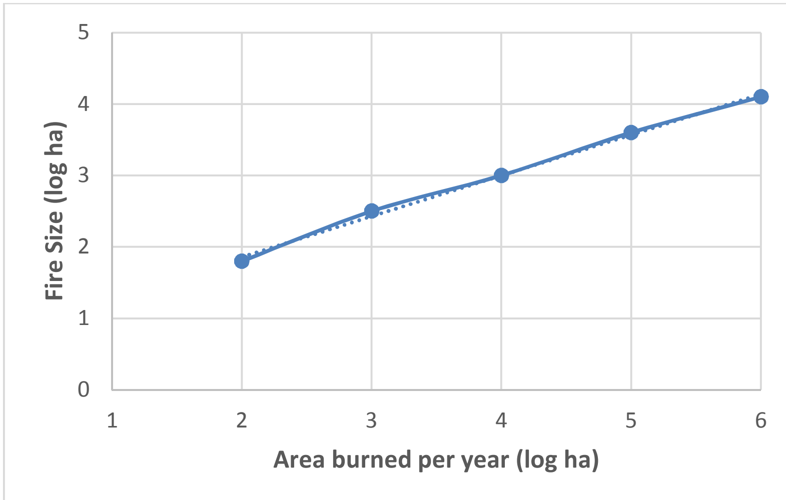
Region	Percentage Burned/Year	Return Interval*	Data Source	Method
Study Area	1.1	87	Area burned each year since 1965 from fire history database	Average of area burned
	1.0	98	Time since fire data since 1965 from fire history database	Negative exponential calculation
	1.1	91		Fitted negative exponential model
	0.7	135	Burn-P3 simulation of historical climate	Mean of burn probability scores
South Slave	1.2	86	Median Time Since Fire data summarized by GNWT**	Negative exponential calculation
North Slave	1.1	93		Negative exponential calculation
Dehcho	0.8	131		Negative exponential calculation
Gwichin	0.7	135		Negative exponential calculation
NWT	0.7	138		Negative exponential calculation
Sahtu	0.6	173		Negative exponential calculation

** Return interval - the expected time between fires on a given hectare – is the inverse of annual area burned*

***J. Hodson, GNWT, unpublished data. Generated using the NWT Fire History dataset with additional fires from Wood Buffalo National Park and fires from the Yukon portion of the range obtained from the Yukon Government's website* *(http://www.community.gov.yk.ca/firemanagement/wfarchives.html). The combined fire data were clipped to the boreal caribou range before running the calculations, therefore estimates reflect the portion of each region that falls within the boreal caribou range, not the entire region.*

Based on historical fire data for the study area, fires are larger and more frequent in hot, dry years, which increases the overall area burned (Figure 2).

Figure 2. Mean Fire Size versus Mean Area Burned



1.3.3.2 Current Forest Fuels

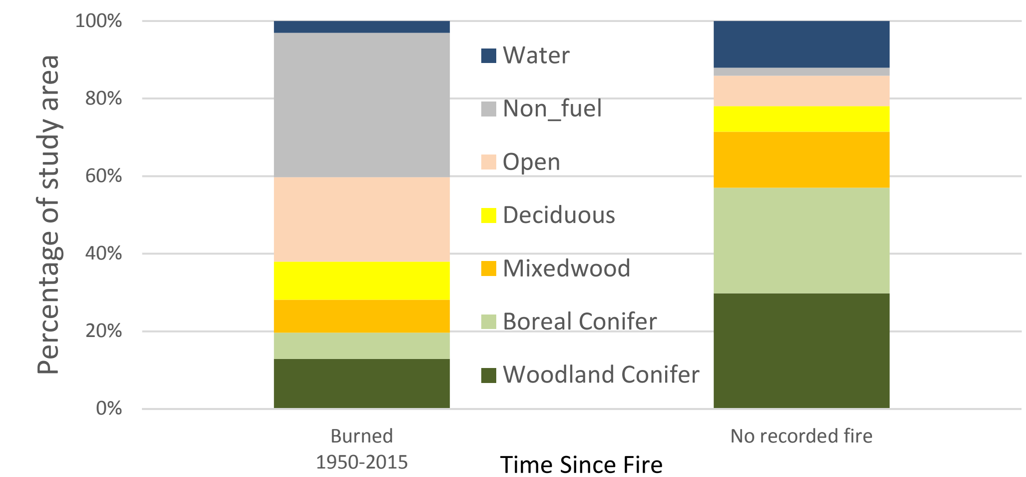
Vegetation cover over a landscape can be described in a variety of ways. In the context of fire regimes, vegetation is classified as fuel types (Table 4 and Appendix 4 of the Burn P3 summary (Appendix B)). We combined time since fire maps with the 2015 fuel cover map (see Section 2.1.2.3) and then grouped and summarized fuel cover for areas with and without fire. Areas with no recorded fires have smaller proportions of non-fuels and open vegetation, suggesting that burned areas revegetate and recover their flammability over time (Figure 3).

Table 4. FBP Fuel Types Found in the Study Area

Fuel Code	Fuel Name	Fuel Type Description	Percentage of Study Area	
			Baseline (2015)	Climate Change Scenarios
C1	Woodland Spruce	Open black spruce stands with dense clumps and lichen understory	23.6%	26.1%
C2	Boreal Spruce	Moderately well-stocked upland and lowland black spruce; includes white and Engelmann spruce but not spruce-sphagnum bogs	19.0%	24.1%
C3	Mature Pine	Fully stocked stands of mature Jack or lodgepole pine	2.1%	2.7%
C4	Immature Pine	Densely stocked stands of immature Jack or lodgepole pine	0.1%	0.2%
C5	Mature Red or White Pine	Mature, moderately well stocked red or white pine stands	<0.1%	<0.1%
M1	Boreal Mixedwood-leafless	25% to 75% deciduous and 75% to 25% conifer; without leaves; can include black spruce, white spruce, balsam fir, subalpine fir, trembling aspen and white birch	11.7%	12.8%

Fuel Code	Fuel Name	Fuel Type Description	Percentage of Study Area	
			Baseline (2015)	Climate Change Scenarios
M2	Boreal Mixedwood-green	As above, but with leaves; green stands have roughly 20% the spread rate of leafless stands (FCFDR, 1992)		
D1	Leafless aspen	Moderate to well-stocked aspen stands, semi-mature; leafless	8.0%	8.6%
D2	Green aspen	Not defined by the original fuel classification because of very low flammability, but used in this project		
O1	Grass		11.9%	12.7%
	Water		5.7%	5.7%
	Non-Fuel		17.1%	6.8
M1 25% conifer	Boreal Mixedwood 25% conifer	Mixedwood stand with 25% conifer	0.7%	0.3%

Figure 3. Composition of Fuel Types in the Study Area in Burned and Unburned Areas*

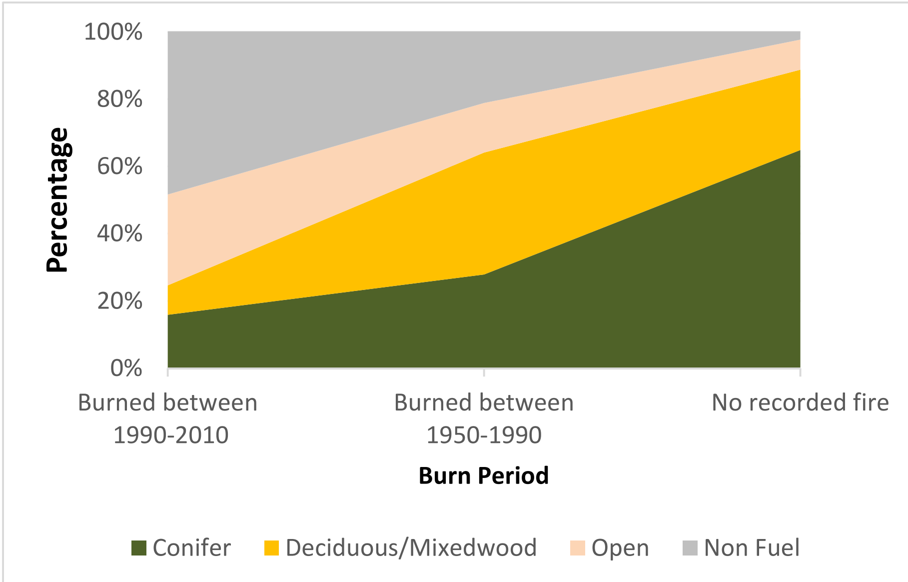


**Fuel types have been grouped as follows: woodland conifer = C1; boreal conifer = C2, C3, C4 and C5; mixedwood = M1 and M1-25C; deciduous = D1; Open = O1; non-fuel = non-fuel codes 119 and 122 and urban code 121.*

1.3.3.3 Fuel Recovery Rates

Based on the fuel composition of ecosystems burned at different times (Figure 4), about 60% of non-fuels recover in about 30 years (based on the midpoint of first and second time periods), leading to a 2%/year recovery rate, with full recovery in roughly 50 years. While limited data suggest a linear recovery, ecological theory suggests that flammability will increase slowly initially and then more rapidly, and that recovery rate will vary with site conditions. Fuel recovery is complex (Van Wagner, 1983) and relatively difficult to predict accurately without resorting to more detailed models (FCFDG, 1992).

Figure 4. Percentage of Area versus Burn Period



1.3.3.4 Tree Species Succession

Deciduous, mixedwood and conifer-leading stands differ substantially in flammability; hence, succession from one forest type to another influences fire behaviour. Different regions of the boreal forest undergo different degrees of succession: in some ecosystems, species composition does not change substantially once a stand is established; in others, deciduous species dominate recolonization and shade-tolerant conifers subsequently dominate (Bergeron and Fenton, 2012; Bergeron et al., 2002; Johnstone, 2003; Weber and Stocks, 1998). Whether or not NWT forests experience similar succession patterns is unclear because studies are lacking.

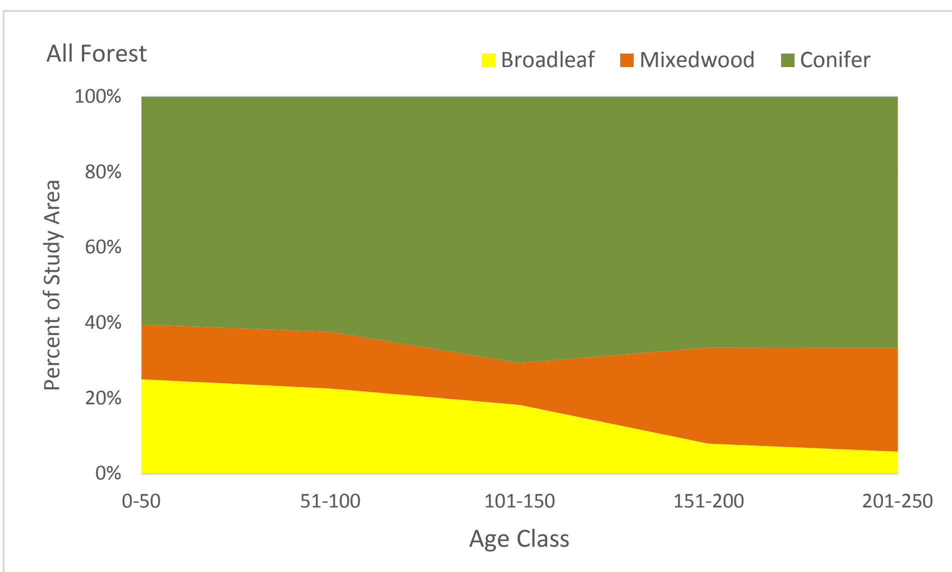
Fire intensity and ecosystem conditions influence regeneration and succession. In mixedwood and deciduous-leading sites, hot fires can kill underground aspen suckers, an important means of aspen recolonization, but hot fires can also expose mineral soil and provide a good seedbed for aspen and white spruce seed blowing in from adjacent stands. Fires of moderate intensity that retain organic forest floor layers can favour white and black spruce regeneration. Aspen seed is small, with limited energy reserves, and has more difficulty germinating in organic material. White spruce has larger seed and fairs better in organic material. Thick organic material favours the large serotinous seed of black spruce.

We explored fuel and forest cover data to look for evidence of succession. In the fuel data, we found evidence of succession of deciduous and mixedwood to boreal conifer stands, but no evidence of succession in high elevation woodland sites (Figure 5).

Figure 5. Composition of Forested Fuel Types in the Study Area in Burned and Unburned Areas

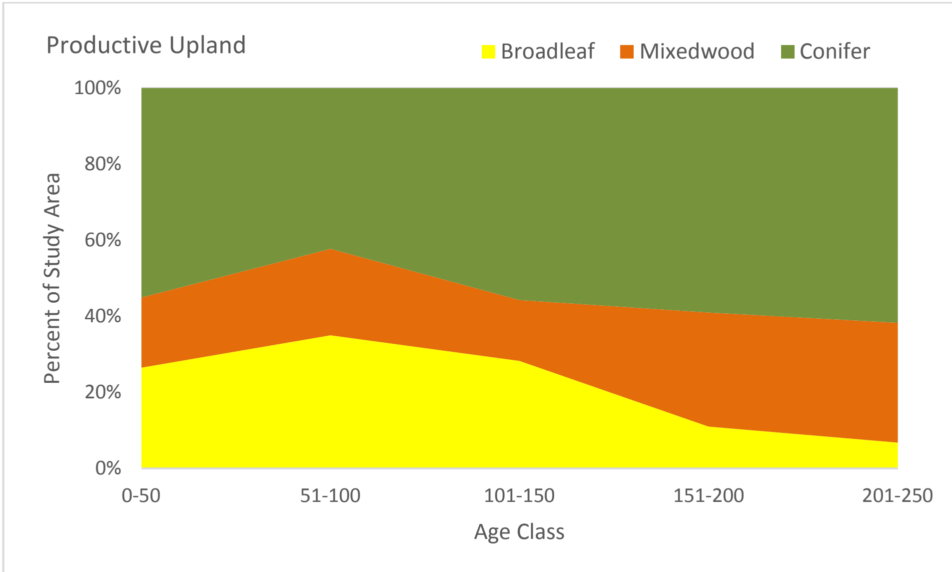
Examined as a whole, NWT forest cover data show little evidence of succession (Figure 6). However, patterns emerge for some ecosystem types. Productive upland forest shows a moderate decline in deciduous-leading stands after about 150 years (Figure 7). Productive wetland forest shows evidence of rapid succession (Figure 8).

Figure 6. Proportion of Deciduous, Mixedwood and Conifer Stands by Age Class in the Study Area*



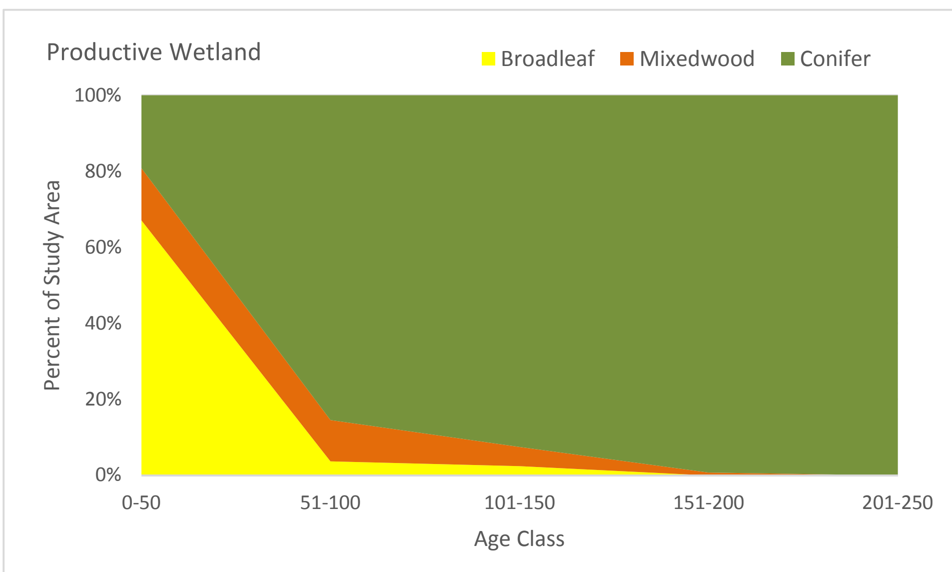
**All productivity classes and canopy density classes are included*

Figure 7. Proportion of Area of Tree Species by Age Class for Productive Upland Forest*



**Data are from the NWT Forest Cover database (see Section 2.1.1.2) and include forests where the landscape position attribute is classified as upland and the canopy density classis either dense or sparse (i.e., excluding open canopies). Productive forest includes site classes 1 to 4; all forest includes site classes 1 to 5.*

Figure 8. Proportion of Area of Tree Species by Age Class for Productive Wetland Forest*



**Data are from the NWT Forest Cover database (see Section 2.1.1.2) and include forests where the landscape position attribute is classified as wetland and the canopy density classis either dense or sparse (i.e., excluding open canopies). Productive forest includes site classes 1 to 4; all forest includes site classes 1 to 5.*

Determining successional change from chronosequence data is subject to error, but represents the best current information.

1.3.4 Climate Change

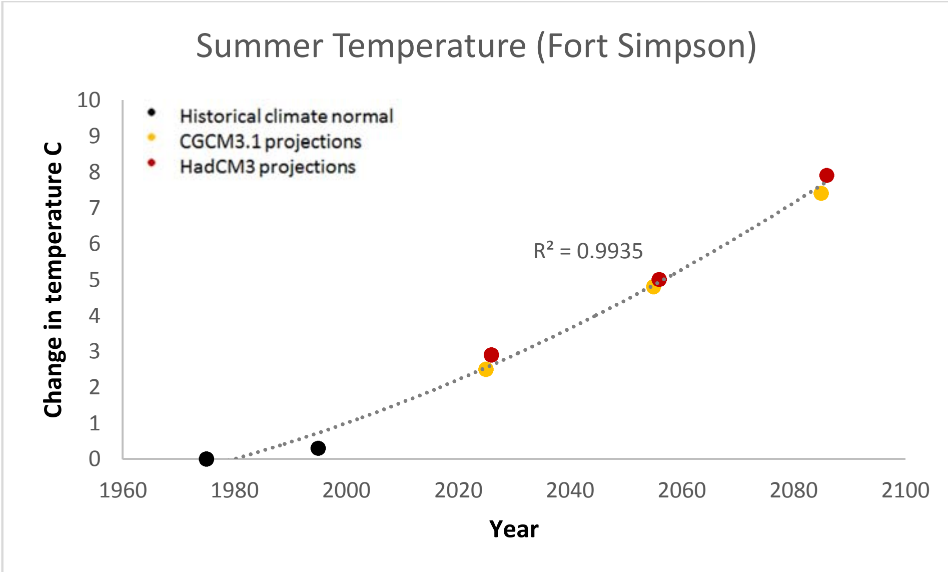
Climate change provides the broad context necessary to assess and manage ecosystems into the future. Successful modelling and management must consider potential changes to disturbance dynamics and ecosystem processes in NWT. A number of global circulation models (GCM) have been developed that integrate interactions between the atmosphere, oceans, land surfaces, and sea ice and incorporate greenhouse gas emissions to predict climate variables (e.g., temperature, precipitation). GCMs differ in terms of specific inputs and relationships used.

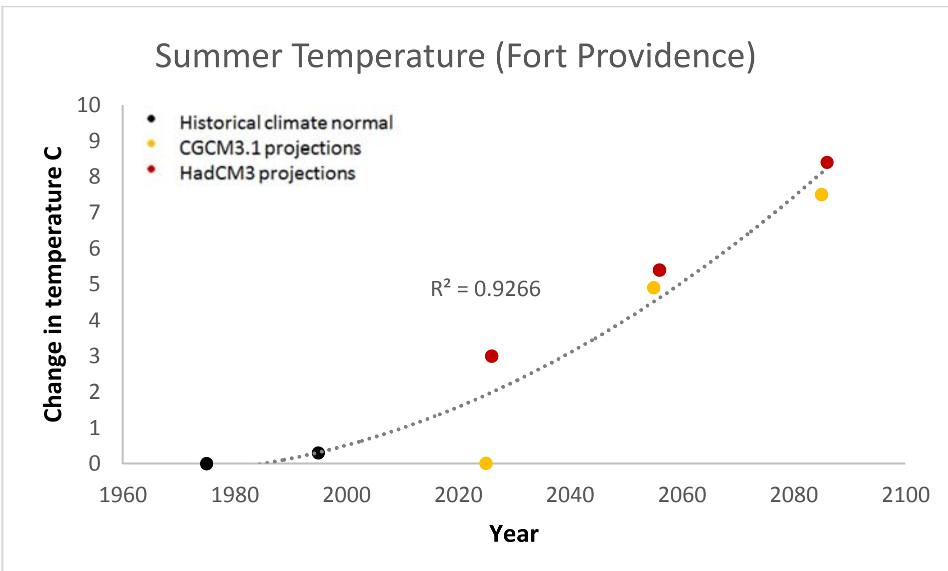
Climate change data were provided courtesy of the University of Alberta's Western Partnership for Wildland Fire Science. For comparative purposes, we used two climate change models: the Canadian Centre for Climate Modelling and Analysis' third generation GCM (CGCM3.1), and the Hadley Centre for Climate Science and Service's third generation model (HadCM3). Those two models were assessed as two of the top five models that provided the most accurate results for Alaska and northern Canada (University of Alaska, 2015; Walsh et al., 2008). They were also two of three models used for assessing extreme fire weather in Canada with climate change (Wang et al., 2015). The HadCM3 model projects hotter and relatively dry conditions into the future. In contrast, the CGCM3.1 model predicts hotter temperatures with relatively high precipitation levels. For comparative purposes, simulations were conducted using both models. We selected the SRESA2 or 'high' CO2 emission scenario to use with the CGCM3.1 and HadCM3 models. The reason for selecting this high scenario was based on the results reported by Wang et al. (2015) that stated "The model results also showed that CO_2 emission scenarios do not contribute significantly to the changes of extreme fire days, which agrees with the results from the X^2 test" and there is an indication that the high CO_2 scenario is perhaps the closest to what is being observed with actual CO_2 emission trends.

1.3.4.1 Climate Projections for NWT

Average annual temperature in southern NWT is projected to increase by about 7 to10°C by 2070 to 2100 from 1960 to1990 historical climate normal (Figure 9). Summer temperature is projected to increase between 7 and 8°C depending on the climate model used (Figure 9) (Wang et al., 2012). Projected patterns in summer temperature are similar between Fort Simpson and Fort Providence.

Figure 9. Projected Increase in Summer Temperature in Southern NWT

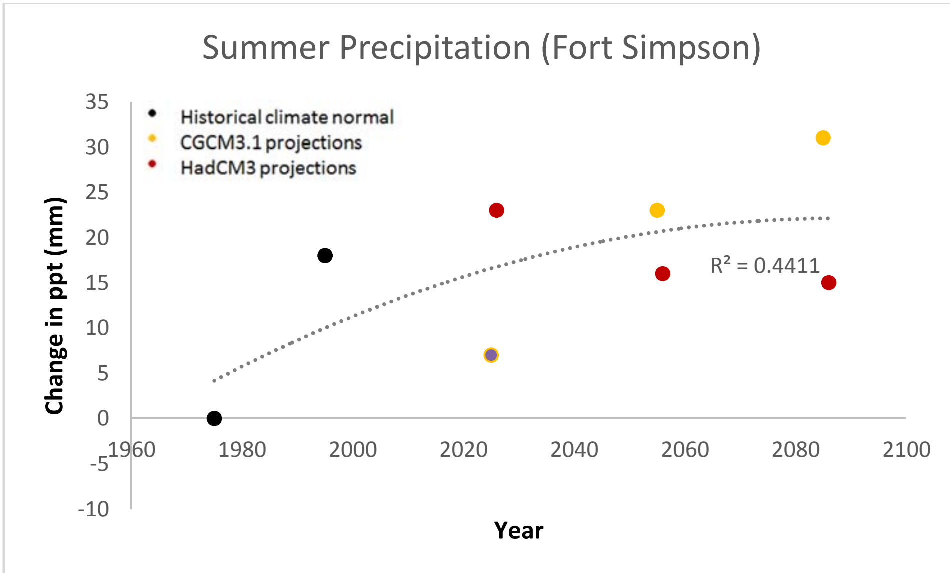


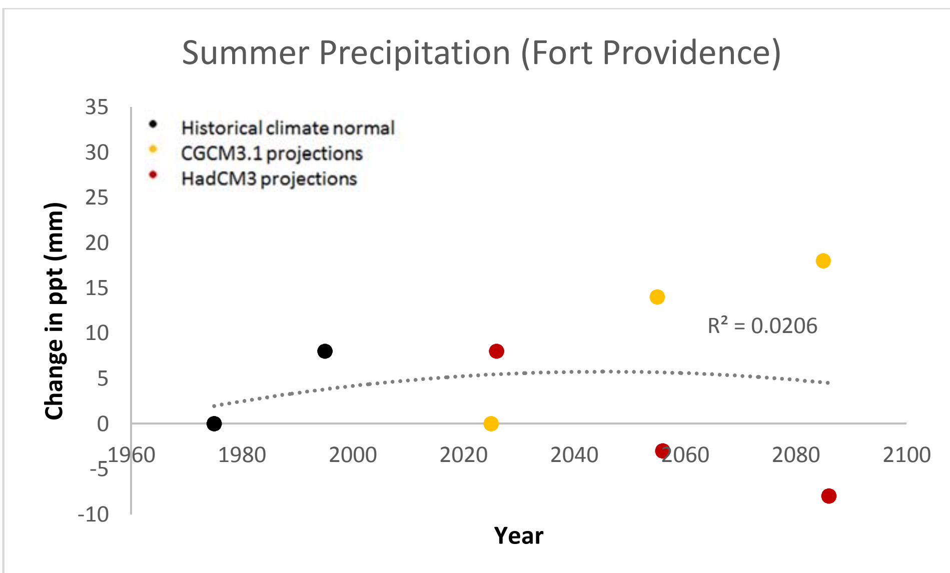


Data are from CGCM3.1 and HadCM3 models with the RCP 85 atmospheric carbon projection; extracted from ClimateWNA (http://www.climatewna.com/).

Summer precipitation is projected to increase initially and then level off over time in Fort Simpson (Figure 10). The two models diverge considerably in projections for Fort Providence, suggesting high uncertainty about whether summer precipitation will increase or decrease (Figure 10).

Figure 10. Projected Change in Precipitation in Southern NWT

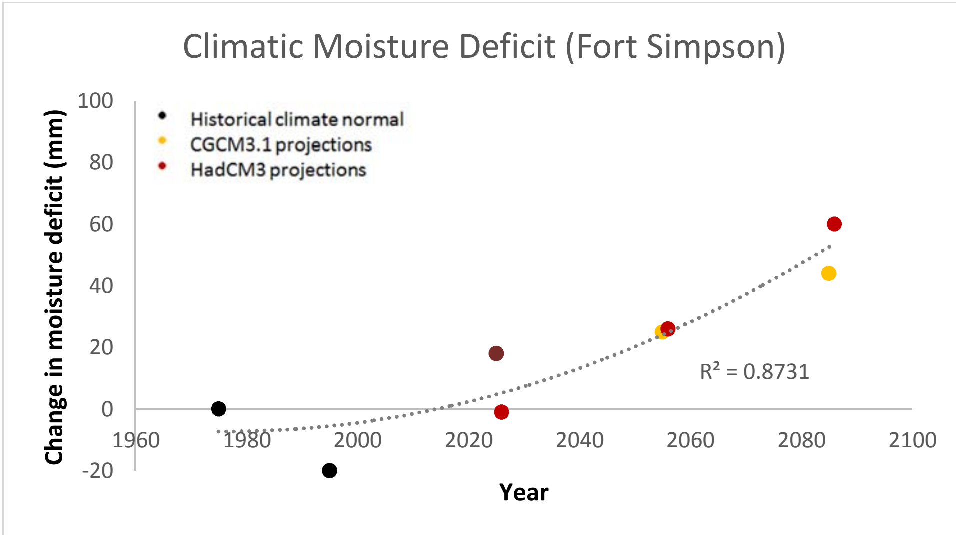


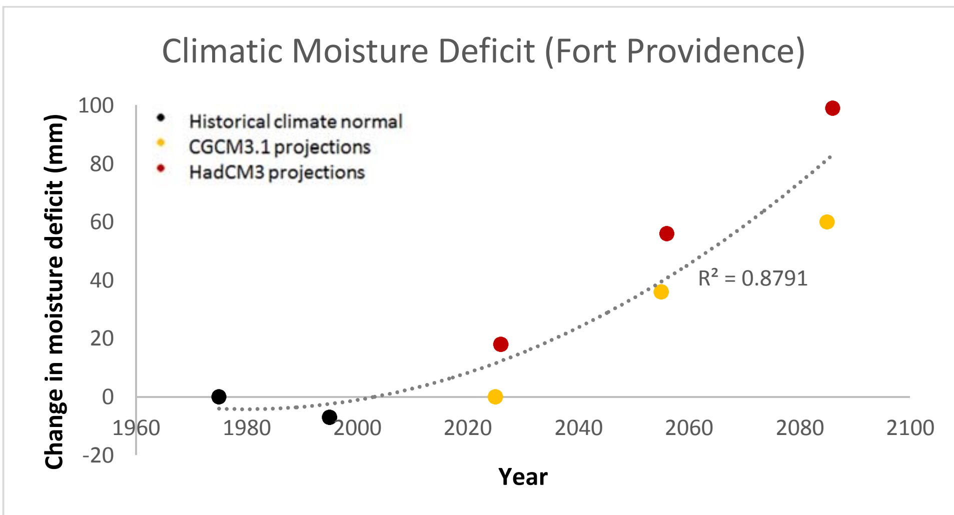


Data are from CGCM3.1 and HadCM3 models with the RCP 85 atmospheric carbon projection; extracted from ClimateWNA (http://www.climatewna.com/).

Critically, however, in both locations, the increased precipitation will be overwhelmed by increased evaporative demand so that the climatic moisture deficit is projected to increase considerably (by 40 to 60 mm in Fort Simpson and 50 to100 mm in Fort Providence) by the end of the century (Figure 11). Climatic moisture deficit measures the moisture needed for vegetation growth from sources other than rain (e.g., soil moisture) to avoid the impacts of drought (Wang et al., 2012). Hence, although summer rain is projected to increase in some areas and with some models, the increased summer temperature means that the probability of severe drought will increase.

Figure 11. Projected Change in Climatic Moisture Deficit in Southern NWT





Data are from CGCM3.1 and HadGEM2-ES models with the RCP 85 atmospheric carbon projection; extracted from ClimateWNA (http://www.climatewna.com/).

1.3.4.2 Potential Impacts of Climate Change

The boreal forest has persisted relatively unchanged for the past 6,000 years. The current rate of climate change, however, may be threatening this resilience as multiple factors potentially trigger cascading effects (Price et al., 2013; Hogg and Bernier, 2005; Chapin et al., 2010).

Increased Disturbance

Disturbances of all types, including fire, insects, and disease are more extensive than at any time historically in North American boreal forests. For example, in the past two decades in Alaskan boreal forests, more area has burned and late-season fires have burned more deeply into the soil (Kasischke et al., 2010). In the Kluane area in Yukon, spruce bark beetles (*Dendroctonus rufipennis*) were kept at endemic levels by cold temperatures until a series of warm summers starting in the 1980s initiated the recent outbreak; beetles, with faster rates of larval maturation due to the increase in temperature, attacked drought-stressed trees (Berg et al., 2006; Garbutt et al., 2006). Flannigan et al. (2005) estimated that area burned in the taiga plains, an ecoregion that largely coincides with boreal caribou range in NWT, would increase by 1.25 to 1.5 times using climate projections from the Canadian Coupled General Circulation Model (CGCM1) and by 1.5 to 2 times using climate projections from the Hadley General Circulation Model (HadCM3). This result matches our finding for the study area of higher area burned for the Hadley than CGCM model. While predicting the future is not possible, CGCM3.1 projections better match ensemble projections, combining results from multiple models and emissions scenarios, than do Hadley projections. Both our study and Flannigan et al. (2005) assumed that carbon-dioxide emissions would be near the high end of projected emissions scenarios—an assumption supported by recent emission trends. Moderate emissions assumptions do not substantially alter mid-century climate projections. Unlike our study, Flannigan et al (2005) do not include likely compensatory feedbacks related to fuel recovery, which may partially account for their higher overall projected burn rate. Although spruce beetle outbreaks have occurred reasonably regularly at about 50-year intervals in the warmer Kenai Peninsula ecosystems, there is only evidence of a single previous outbreak in the Kluane area over the past 250 years.

To date, NWT boreal forests have not experienced the increases in fire frequency and insect outbreaks seen to the west. However, with warmer summers and increased drought projected for NWT, both fires and insect outbreaks are likely to increase (Price et al., 2013). For example, the median number of fire spread days for the study region, already one of the highest in the Canadian boreal at 9 days/year, is projected to more than double to 22 days/year by the end of the century (Wang et al., 2015). Spruce bark beetles are currently endemic in NWT, attacking weakened and windthrown trees. However, there is the potential for warmer temperatures and timber harvest activities to increase populations to the point that they can overwhelm healthy trees as they have in Alaska and Yukon, where they triggered the largest outbreaks ever recorded (Price et al., 2013).

Permafrost Change

Much of the discontinuous permafrost within Canada's boreal ecosystems is projected to be degraded by the end of the century (Price et al., 2013). As permafrost thaws and subsides, low-productivity ecosystems become water-logged, leading to extensive tree mortality, and release of methane (Price et al., 2013). Poorly-drained lowland forest ecosystems will likely shift to wetlands, while better-drained ecosystems may recover over time and become more productive following aeration and nutrient release (Price et al., 2013). Some regions of NWT have already experienced permafrost degradation (e.g., 10 – 50% degradation in the Mackenzie Valley, decrease from 72 to 40% permafrost at Scotty Creek (Price et al., 2013).

Fires and human activities interact with permafrost. Hot fires accelerate permafrost degradation by burning organic matter, decreasing albedo and warming the soil surface (Price et al., 2013). Linear disturbances, including seismic lines and pipelines, can form grids of permafrost-free wetlands that can influence surrounding ecosystems (Price et al., 2013). Old growth black spruce ecosystems are most resistant to permafrost loss due to a thick organic layer, abundant soil moisture and large trees that decrease snow cover and increase winter cooling; much existing permafrost remains frozen due to protection by undisturbed forest (Price et al., 2013).

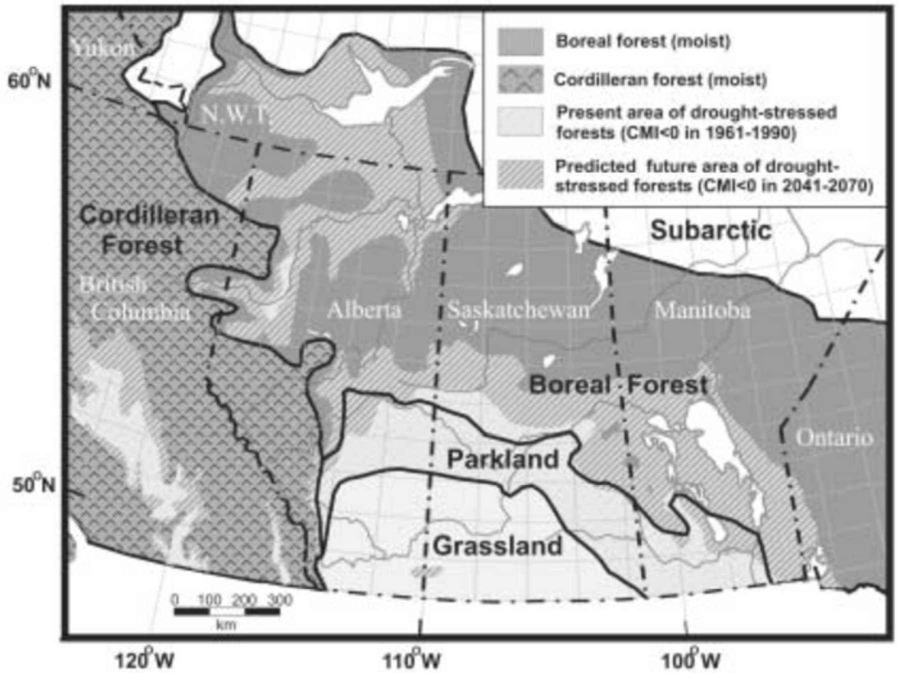
Regeneration Challenges

The increased disturbance frequency and increased summer temperatures and/or changed patterns of precipitation have already altered tree regeneration and succession trajectories in some portions of the boreal forest. In southwest Yukon, stands on south-facing slopes recently shifted from monotypic white spruce forests to mixed spruce and aspen or entirely aspen-dominated stands following a fire (Johnstone et al., 2010; Chapin et al., 2010). Post-fire growth of spruce and aspen has been slow and related to variation in precipitation, suggesting vulnerability to drought (Hogg and Wein, 2005). Similarly in Alaska, except on poorly-drained sites, severe fires have disrupted black spruce regeneration, and shifted successional trajectories from spruce-to-spruce replacement to trajectories dominated by deciduous seedlings, with very little spruce recruitment at all on dry sites (Kasischke et al., 2010). White spruce growth rates have declined with warmer summers. In some areas of Alaska and Yukon, growth is now limited by drought rather than nutrients or temperature (Hogg and Wein, 2005; McGuire et al., 2010). NWT lies within the western portion of the North American boreal biome that is more vulnerable to drought compared to the eastern portion that receives considerably more precipitation due to lake and ocean influences and storms tracks from the United States (Price et al., 2013).

Ecosystems can change their structure, composition and function rapidly during a 'regime shift', where, for example, a previously forested ecosystem fails to follow its historical successional pathway and instead regenerates into grassland following fire (Price et al., 2013). There are predictions that parts of the southwest boreal forest, including southern NWT, are potentially on the cusp of a non-linear regime shift to shrub and/or aspen parkland (Hogg and Bernier, 2005; Chapin et al., 2010). Historically, continuous boreal forest ecosystems are generally limited to regions with sufficient precipitation to replace annual evapotranspiration, whereas drier areas with climate moisture deficits are occupied by aspen parkland (Hogg and Bernier, 2005). The tipping point for a regime shift could occur when precipitation falls short of the water demands of an ecosystem (as represented by annual potential evapotranspiration), enhanced by cumulative effects; for example, conifers fail to regenerate after fire, or drought-stressed trees become more susceptible to insects and disease (Price et al., 2013; Hogg and Bernier, 2005). Such a shift would have cascading effects as surplus water would no longer be available for hydrological systems, creating streamflow, stable lake levels and high water tables that lead to bog formation. Instead, if precipitation declines below demands, streams may lose flow seasonally, lakes may dry and become saline, and bogs may be replaced by parkland and grassland ecosystems (Hogg and Bernier, 2005). Conifers may be absent from most places, replaced by aspen (Hogg and Bernier, 2005).

Some projections suggest that precipitation will drop below demand along the current southern extent of boreal forests in the prairie provinces, and also along the rivers of northern Alberta and adjacent southern NWT, including the study area as well as in parts of Yukon and Alaska (Figure 12; from Hogg and Bernier, 2005). Although uncertainties remain high about the rate of change and extent of compensation via redistribution of species (e.g., white spruce could replace black spruce on some sites), potential drops in precipitation will increase the vulnerability of southern NWT forests to a regime shift and will reduce the probability of successful regeneration to coniferous forests.

Figure 12. Projected Change in Area of Drought-stressed Forests that may Undergo a Regime Shift from Coniferous to Parkland Ecosystems by the Middle of the Century



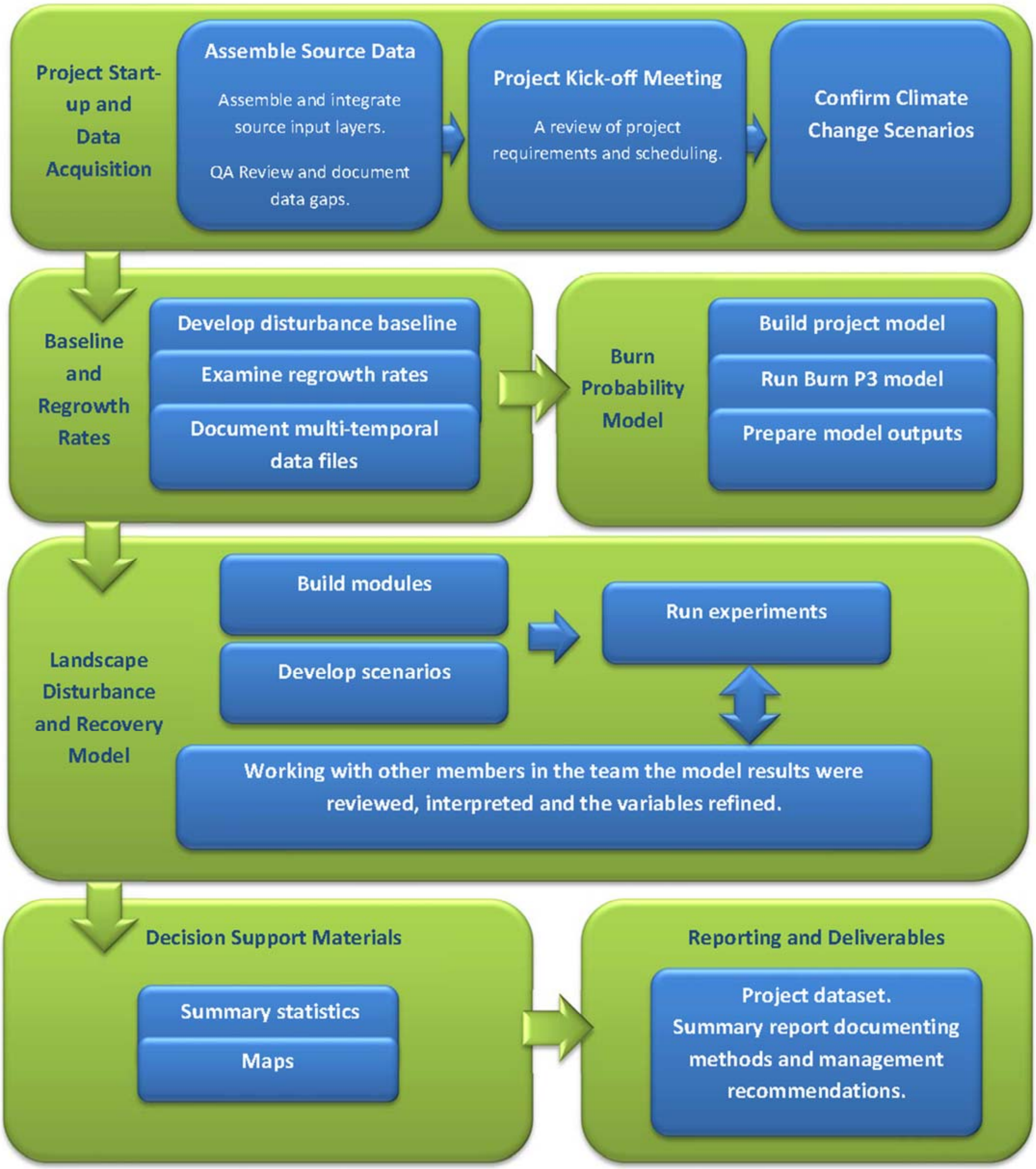
From Hogg and Bernier, 2005

2.0 METHODS

The potential effects of forest fires and timber harvesting under different climate scenarios were modelled to examine the implications to boreal caribou habitat and timber supply over time. A key initial objective was to identify areas which could be susceptible to fires in the near-term (e.g., the next 25 years) and assess the implications related to caribou management in the context of both timber harvesting and fire management. Burn-P3 was used to develop burn probability models and SELES was used to simulate forest landscapes to assess the impacts and interactions of fires and timber harvesting under different climate change scenarios. The project also examined the potential recovery of disturbed caribou range over time. The resultant models and derivative data products will help guide GNWT-ENR decision-making towards maintaining boreal caribou critical habitat as identified in the Recovery Strategy and mitigating the negative effects of future fires and timber harvesting.

Figure 13 provides an overview of the main project phases and their associated tasks. The methods and approaches used to develop the modelled results are explained in detail in the following sections.

Figure 13. Project Work Plan Overview



2.1 Source Data

Various data layers were assembled to help model both the current and future landscapes using different climate change, fire, and linear feature recovery scenarios. The following data were used or evaluated over the course of the project.

2.1.1 Landbase

2.1.1.1 EOSD Integrated Land Cover

The land cover dataset from Earth Observation for Sustainable Development of Forests (EOSD) was provided by GNWT. It covers most of the NWT and Yukon, as well as western Nunavut and northern portions of British Columbia, Alberta, Saskatchewan and Manitoba. The original EOSD mosaic dataset was compiled in 2000 based on the classification of Landsat imagery at a 25 metre pixel resolution. An enhanced version of the EOSD land cover dataset, covering the southern half of the study area, was developed in 2007 using a 30 metre pixel resolution. The two datasets were integrated and resampled (a filter was run on the dataset and a neighbourhood analysis conducted to populate 'no data' cells with the attributes of their surrounding cells) by GNWT to yield the enhanced EOSD land cover dataset at 30 metre pixel resolution (Figure 14). The enhanced EOSD land cover dataset was used to examine the recovery rates of disturbances in the study area by intersecting the land cover with the disturbed linear features datasets (Section 2.5).

2.1.1.2 NWT Forest Resource Inventory

GNWT provided the NWT Forest Resource Inventory (FRI) layer (Figure 15), which was used to evaluate the land base where coverage was available. The NWT FRI layer uses the territory's Land Cover Classification scheme and stand characteristics to delineate polygons. Classifications include land base, land cover type, land position, vegetation type, vegetation density, and species type(s). The NWT FRI land cover dataset was used to examine the recovery rates of disturbances in the study area by intersecting the land cover with the disturbed linear features datasets (Section 2.5).

2.1.1.3 Elevation and Slope

Elevation information was obtained from the Canada Digital Elevation Data (CDED) dataset (Figure 16), which has a raster resolution of 100 metres. For the purpose of this project, the elevation model was resampled to 250 metres. Slope (Figure 17) was derived from this resampled dataset.

2.1.2 Fire

2.1.2.1 Historical Fire Data

Historical fire data were provided by the GNWT for fires from 1950 to 2015. GNWT also provided a supplemental fire history dataset that covered Wood Buffalo National Park, located southeast of the study area. The team acquired additional fire history datasets to gain full coverage of the buffered study area, which extended into B.C. and Alberta. These additional datasets included the Alberta Agriculture and Forestry historical wildfire database and the B.C. Wildfire Service historical fire perimeters. The fire history data were unioned using ArcGIS, and when there was overlap in fire polygons, the date of the most recent fire was used. Figure 18 shows the integrated fire history dataset.

2.1.2.2 Fire Cause Database

The fire cause dataset (supplied by the GNWT) denotes the cause of fires, using the fire key or fire number found in the historical fire dataset as a reference. This dataset records fire cause from 2010 to 2015 throughout the NWT and includes fires caused by industry, humans and natural means. The vast majority (approximately 95%)

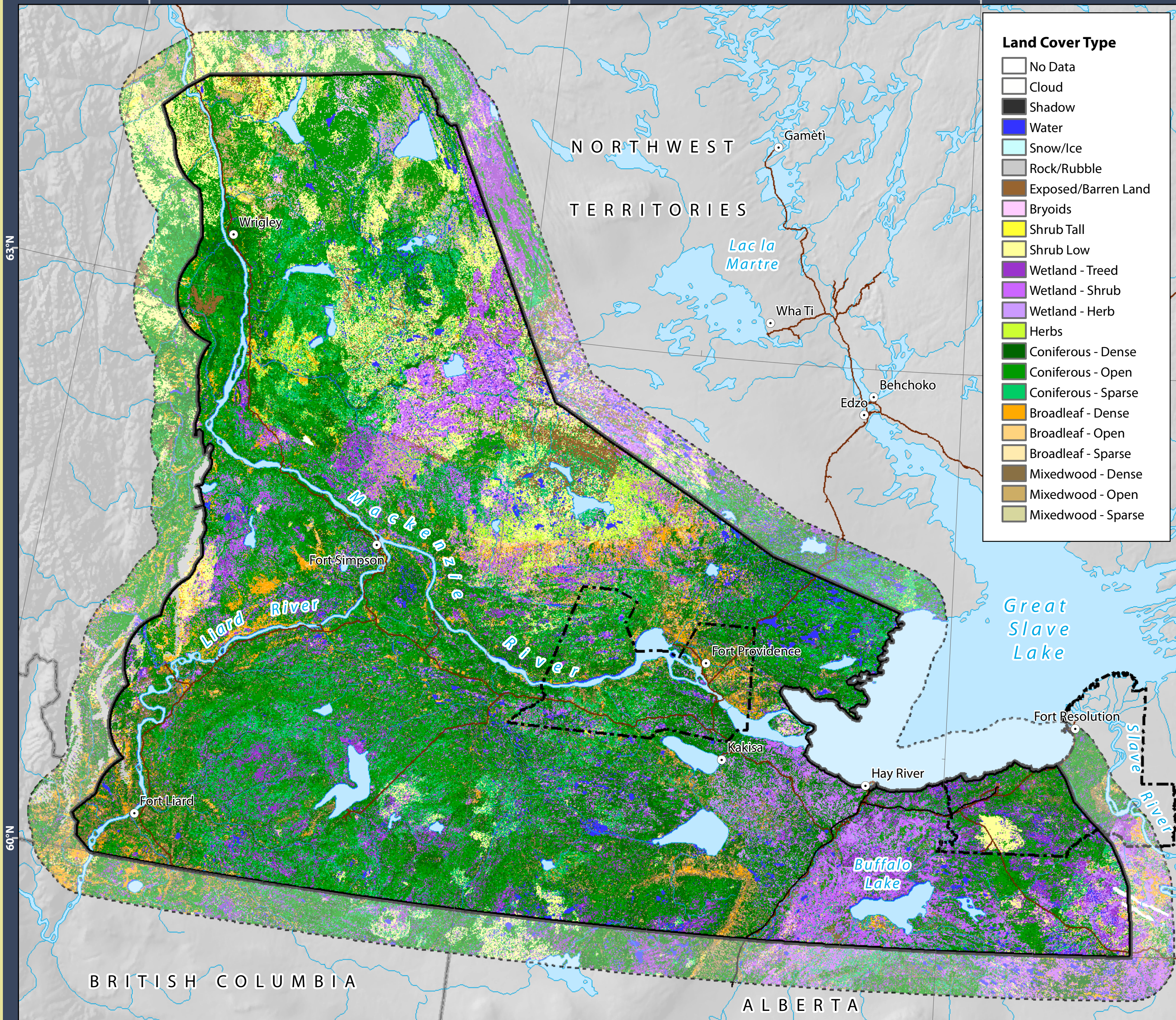


Figure 14

EOSD Integrated Land Cover Dataset

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Earth Observation for Sustainable Development of Forests

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

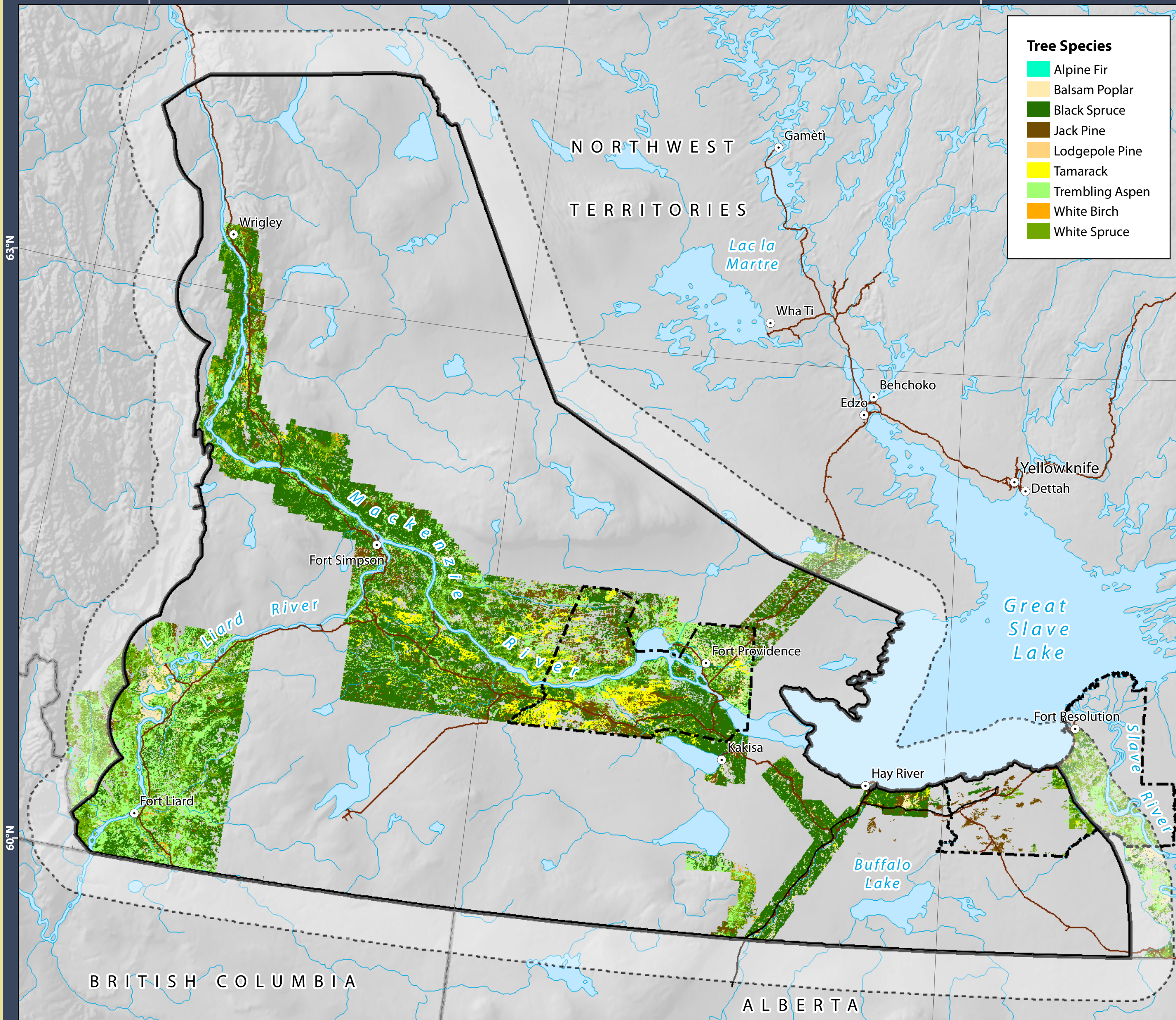


Figure 15

NWT Forest Resource Inventory

Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Northwest Territories Forest Resource Inventory

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

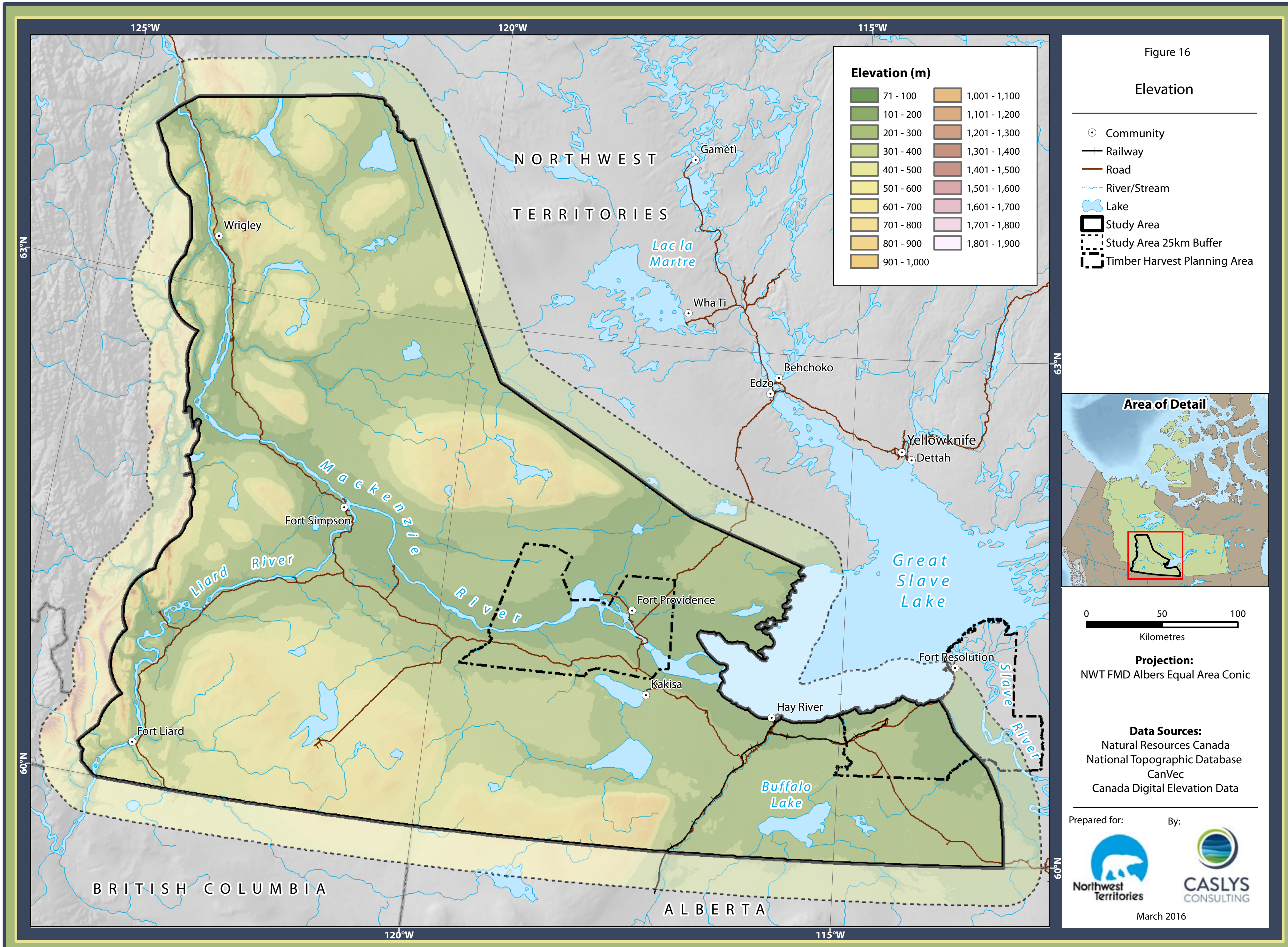


Figure 16

Elevation

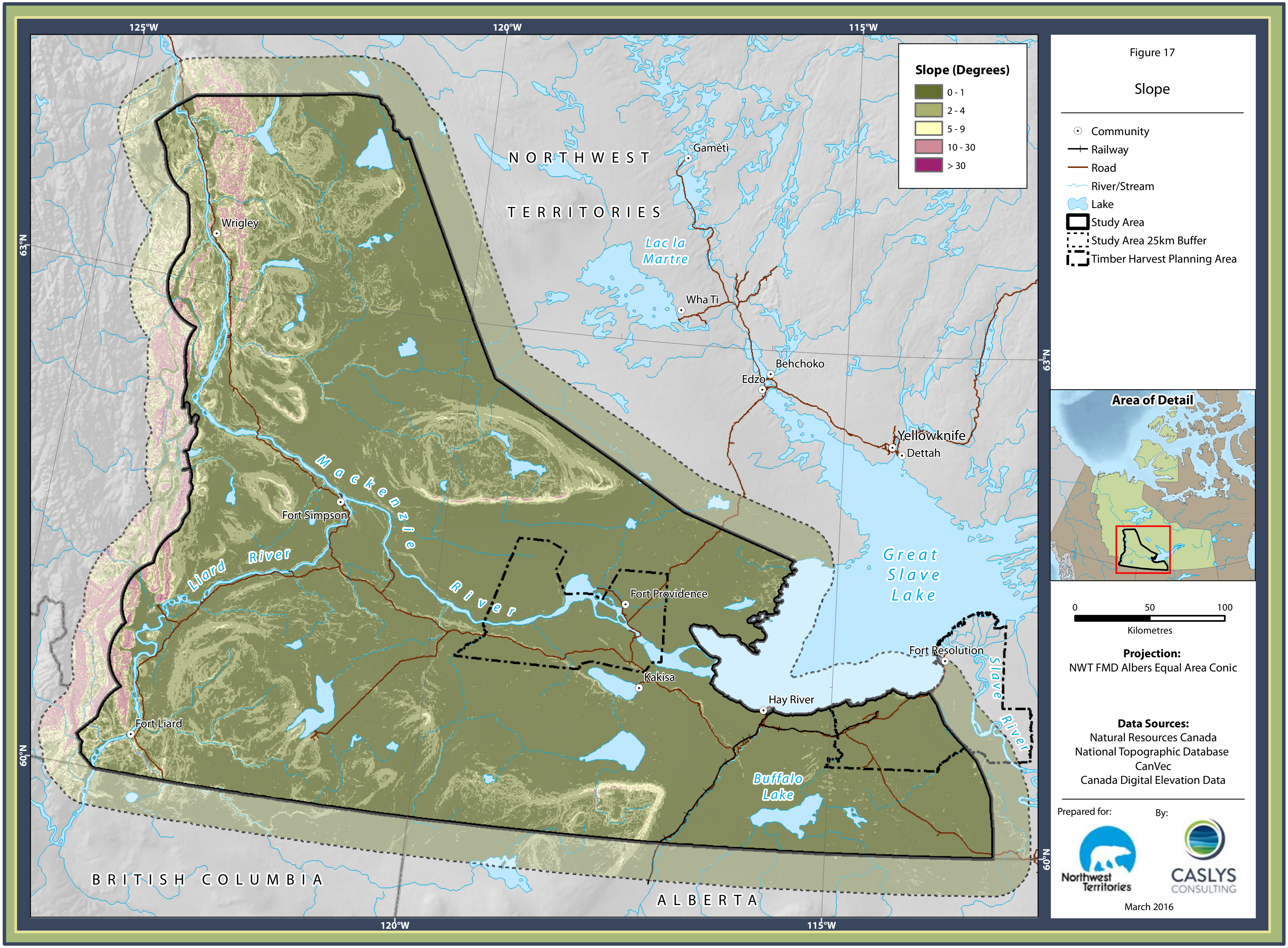


Figure 17
Slope
Slope (Degrees)
0 - 1
2 - 4
5 - 9
10 - 30
> 30
Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Area of Detail
0
50
100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Canada Digital Elevation Data
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
125°W
120°W
115°W
63°N
60°N
Gamètì
Wrigley
Lac la Martre
Wha Ti
Behchoko
Edzo
Yellowknife
Dettah
Mackenzie River
Fort Simpson
Liard River
Great Slave Lake
Fort Providence
Fort Resolution
Slave River
Kakisa
Hay River
Fort Liard
Buffalo Lake

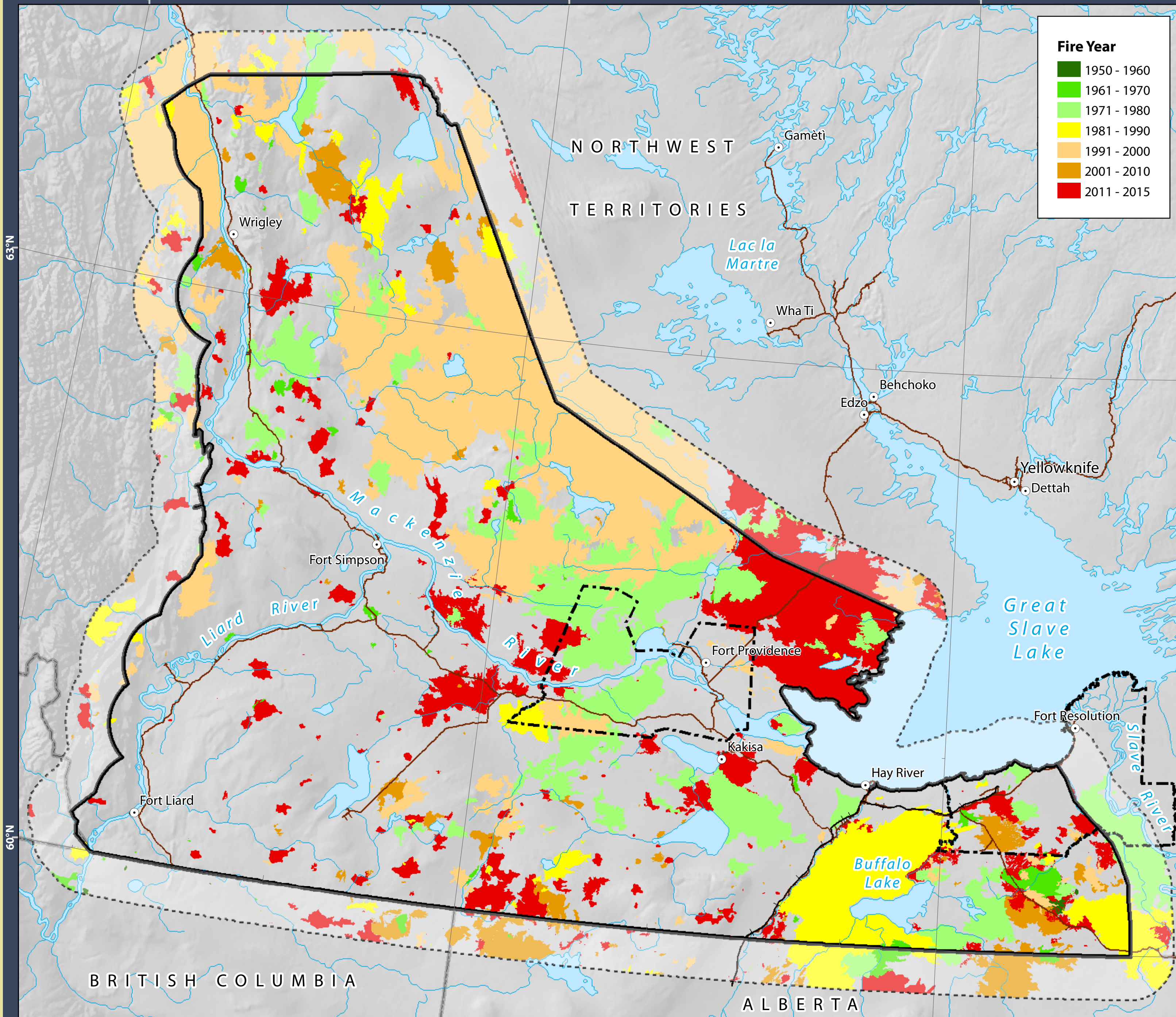


Figure 18

Integrated Fire History Dataset

- Community
- Railway
- Road
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

0 50 100

Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Alberta Agriculture and Forestry
BC Wildfire Service

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

of fires in the dataset started from natural causes, such as lightning strikes. The fire cause dataset was joined with the integrated fire history dataset (Figure 18).

2.1.2.3 Fuel Types

To evaluate fire behaviour, GNWT provided a Canada-wide fuels layer dataset utilizing fuel type codes found in the Canadian Forest Fire Behavior Prediction (FBP) System[2]. This system, developed by the Canadian Forest Service, stratifies land cover based on flammability (Table 4; Figure 19). The fuel types used in the Baseline (2015) scenario were modified to take into account recent fire history; specifically, fuel types in areas of recent burns (<= 5 years) were re-classified to non-fuel and recent burns >5 and <=10 years old were re-classified to a mixed-wood fuel type with a 25% conifer component. Following fire, much of a burned area is described as non-fuel or as open. Most of these areas are likely to revegetate and recover their flammability over time.

2.1.3 Forest and Timber Harvest

2.1.3.1 Timber Harvest Planning Areas

GNWT has set up two Timber Harvest Planning (THP) areas; Fort Providence and Fort Resolution. These THP areas correspond to the FMAs recently signed with aboriginal companies to stimulate the timber harvest industry in the southern NWT. The Fort Providence and Fort Resolution[3] FMA areas cover 7,604 km^2 and 3,604 km^2, respectively, for a total of 11,208 km^2.

2.1.3.2 Timber Access and Harvest Blocks

GNWT provided timber harvest access roads and existing and planned harvest blocks for the Fort Providence and Fort Resolution THP areas (Figure 20). For the Fort Providence THP area, we also received the timber harvest compartment areas from the 25 year strategic plan, used to manage access and timing of harvest blocks. In addition to the existing and proposed harvest blocks for the THP areas, GNWT provided additional harvest cut blocks found within the study area from 2002-2013.

2.1.4 Human Disturbance

2.1.4.1 Environment Canada Human Disturbance

The human disturbance dataset used to develop the landscape projections was the boreal caribou ecosystem anthropogenic disturbance layer from Environment Canada (Figure 21). The dataset, provided in both linear and polygonal format, is current to approximately 2010, and represents human disturbance footprints (e.g., roads, seismic lines) captured from 1:50,000 scale Landsat image interpretation. This dataset was used to ensure consistency between the results of this project and the disturbance/caribou range relationship developed for the Recovery Strategy.

[2] The FBP System fuel type data was derived from vegetation inventory data that was derived from remote sensing imagery and other ancillary data layers from the early 2000s. We re-classified burn polygons assuming a cut-off date of 2005; however, this assumption means that potentially some polygons should have been classified as M-1 25%C rather than the attribute present in the FBP dataset. From a burn probability perspective, there is no anticipated noticeable effect in the final results as these potentially affected areas would still ignite and burn in each simulated fire.

[3] The total area of the Fort Resolution THP is 7931 km^2. A portion (4327 km^2) of the Fort Resolution THP area falls outside the study area. This area has been excluded from the statistics.

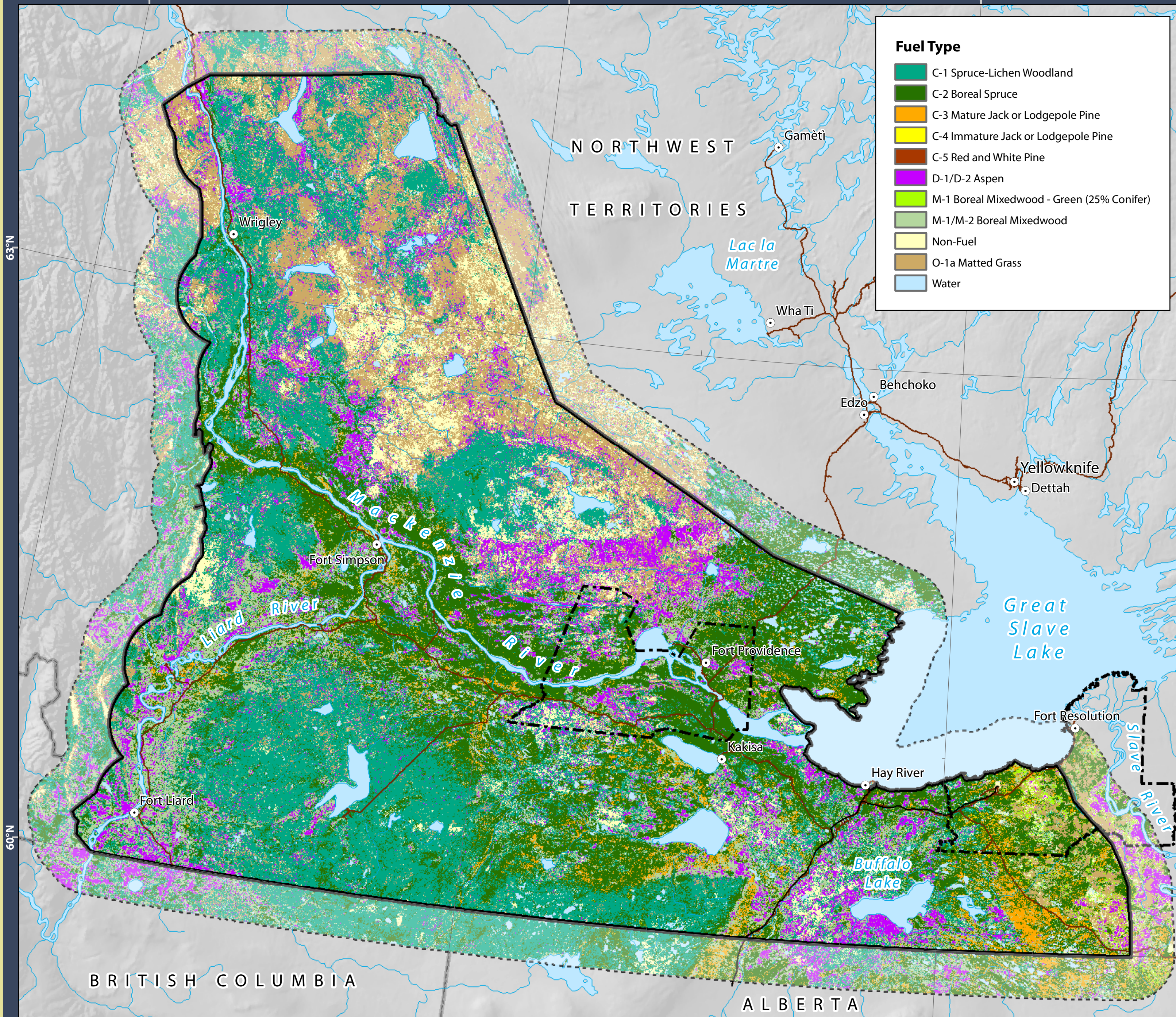


Figure 19

Fire Behaviour Prediction (FBP) System Fuel Types

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Ember Research Services Ltd

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

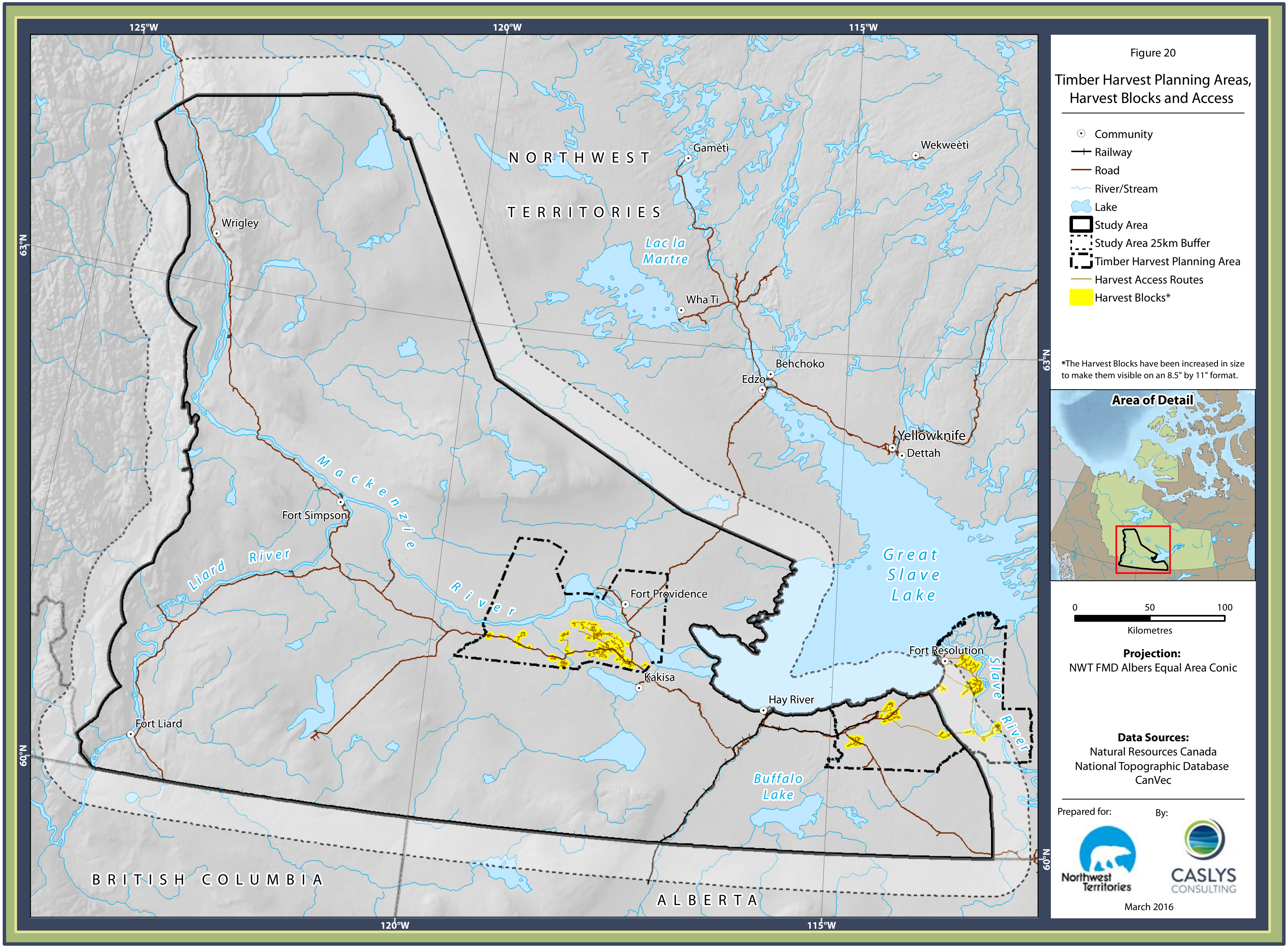


Figure 20

Timber Harvest Planning Areas, Harvest Blocks and Access

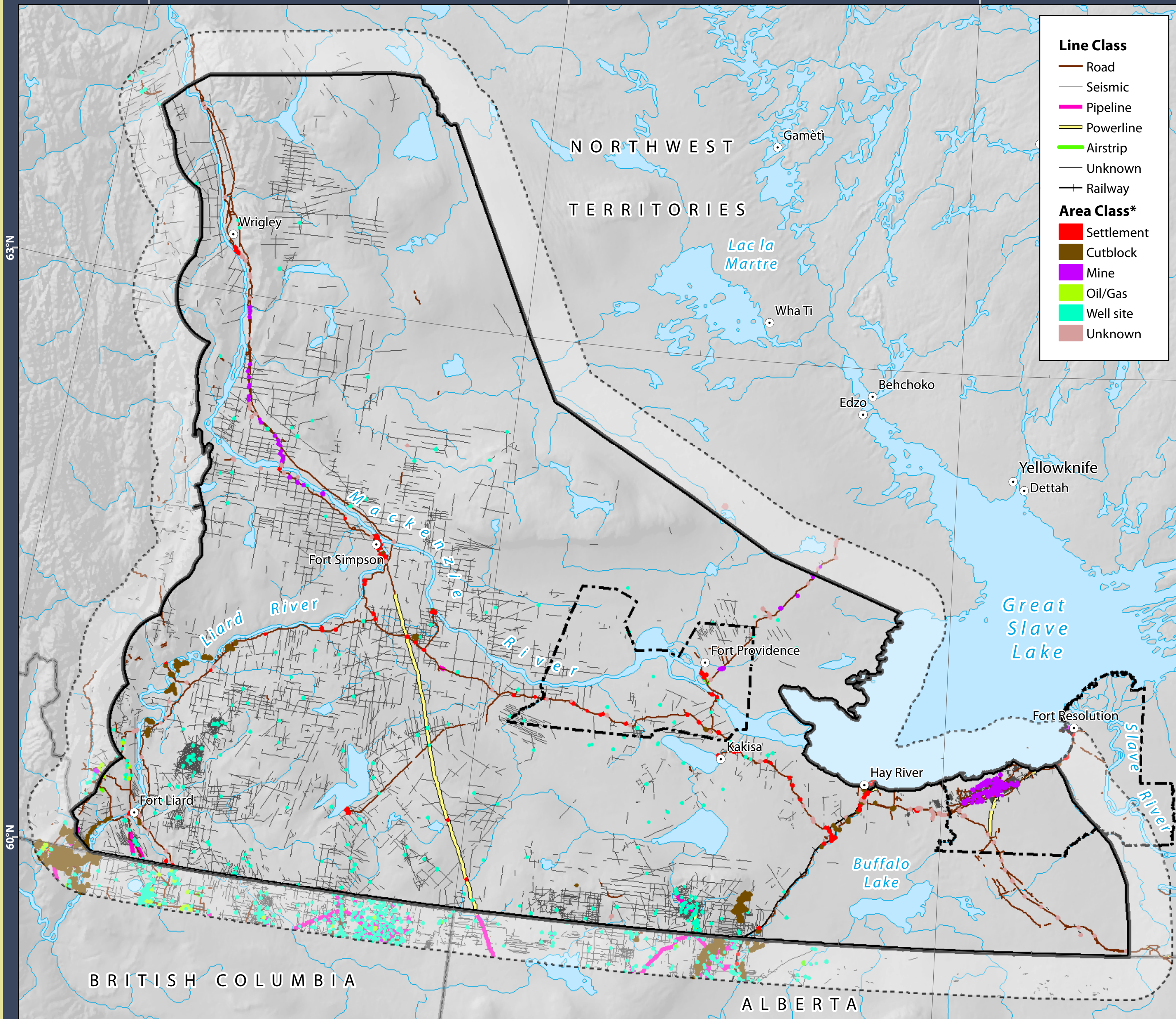


Figure 21

Environment Canada
Human Disturbance Dataset

Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

*The disturbance areas have been increased in size to make them visible on an 8.5" by 11" format.

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Environment Canada

Prepared for: Northwest Territories
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March 2016

2.1.4.2 Other Human Disturbance

In addition to the Environment Canada human disturbance dataset, other human disturbance footprint layers were utilized as reference layers including: linear feature datasets from the National Energy Board (NEB) and Natural Resources Canada (NRCan), CanVec transportation lines (i.e., roads, railways), and communities supplied by GNWT. In particular, the NEB seismic lines were used, along with the Northwest Territories FRI layer, to examine recovery rates of linear features on the landscape depending on land cover (see Section 2.5).

2.1.5 Weather Zone Grids

Four weather zones were delineated for the study area (Figure 22). These weather zones are based on the ecoprovince boundaries as described by Marshall et al. (1999). Originally, the intent was to follow the method used for delineating weather zones as described in Armitage (2014), which resulted in 18 weather zones for this study area. However, as a result of discussions with CFS staff, it was determined that the resolution using the 18 zones was too fine for the climate change models and that the broader ecoprovinces were more appropriate (Evan Delancey and Marc Parisien, pers. Comm. February, 2016). For the weather zones, the only variation from the ecoprovince boundaries is that a thin wedge of an ecoprovince along the western edge of the study area was incorporated into the westernmost weather zone to avoid creating a fifth additional small zone.

2.1.6 Other Cartographic Layers

A variety of other spatial data layers were used or evaluated over the course of the project:

- ecoregions from the Forest Management and Wildlife divisions of Environment and Natural Resources;
- topographic contours and hydrographical features from CanVec; and,
- parks and protected areas from GNWT

2.1.7 Data Acquisition and Organization

Most source datasets were received from Kathleen Groenewegen at GNWT from November 2015 to February 2016. The datasets were reviewed to ensure all data necessary to cover the study area were present and projected to a standard coordinate system. The data layers were projected to a custom projection provided by GNWT based on Albers Equal-Area Conic (NWT_FMD_AEAC).

To process the data in the SELES landscape model, certain data layers were clipped to the buffered study area, resampled to 250 metre resolution, and converted to ASCII raster format. Some layers were multiplied by a scale factor when loaded into SELES to convert real numbers to truncated integer values, as required by the software.

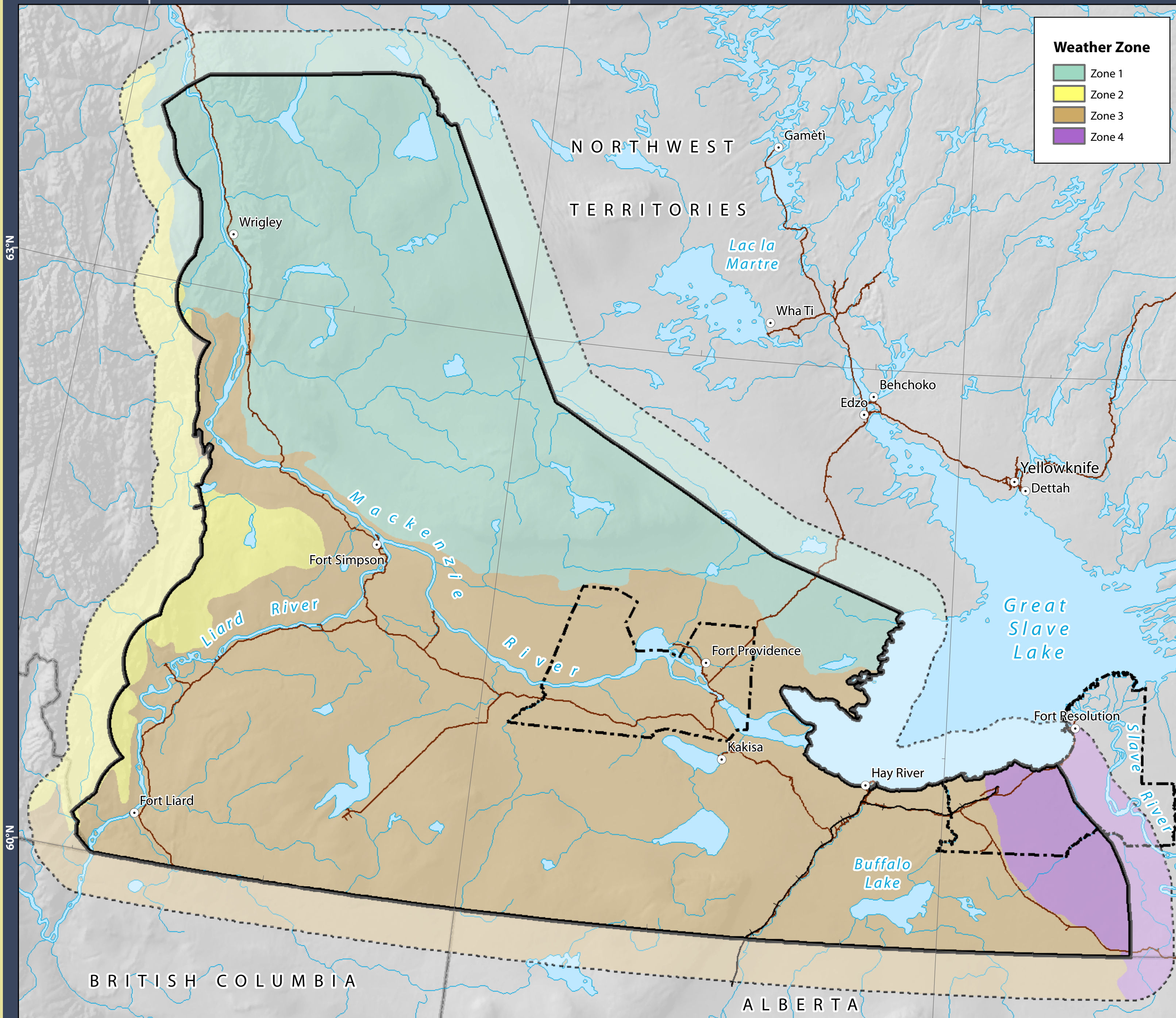
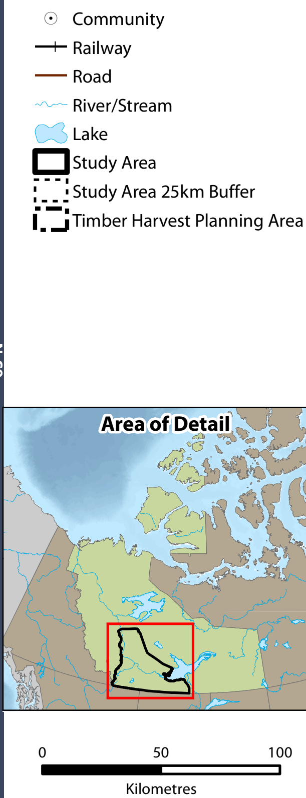


Figure 22

Burn-P3
Weather Zones



Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Ember Research Services Ltd

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

2.2 Burn-P3 Model

The following sections provide an overview of the methods used to conduct the Burn-P3 analyses for the study area. Additional detail related to the methods used to generate the analyses may be found in Appendix B.

The model evaluates the relative likelihood of burning for every given point (represented in this analysis as a 250 m^2 cell) in a landscape. A burn probability value (expressed as a percentage) is derived by modeling the ignition and spread of individual wildfires greater, or equal to, a predetermined size for a series of iterations (Parisien et al., 2014). The minimum fire size used in this analysis was 30 hectares. Fire behaviour and fire rate of spread calculations are performed using the Prometheus wildland fire simulation model (Tymstra et al., 2010) which utilizes the Canadian Fire Behavior Prediction (FBP) System for all fire behaviour calculations and outputs. The area burned by each simulated fire during each iteration of the simulation is recorded and the burned areas are compiled into a cumulative grid to quantify probability of a given cell burning. Each iteration represents a year and the model runs thousands of iterations to derive the burn probability for a given scenario. The burn probability for each individual cell is calculated by recording the total number of times the cell burns and then dividing this number by the total number of iterations in the Burn-P3 simulation.

Burn-P3 and PrometheusCOM were used to generate the burn probability and fire intensity analyses. The following software versions were utilized for this project:

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

In addition to quantifying the wildfire burn probability as of the year 2015, the Burn-P3 program was used to estimate future burn probability based on potential fire weather conditions generated from two different climate change models for two different future time periods.

The following Burn-P3 scenarios were run for this NWT study area:

1. Baseline (2015)
   This scenario utilized the fuel and weather data as it existed in the fall of 2015 and therefore generated the burn probabilities over the landscape based on the current conditions within the study area.

Climate Change Scenarios

2. Baseline (Model)
   A model-derived baseline used for the climate change scenarios.

3. CGCM 3.1 (2050)
   Model : Canadian Center for Climate Modelling and Analysis (CGCM3.1)
   Time Period: 2031 – 2060

4. CGCM 3.1 (2080)
   Model : Canadian Center for Climate Modelling and Analysis (CGCM3.1)
   Time Period: 2061 – 2090

5. HadCM3 (2050)
   Model : Hadley Centre for Climate Prediction (HadCM3)
   Time Period: 2031 – 2060

6. HadCM3 (2080)
   Model : Hadley Centre for Climate Prediction (HadCM3)
   Time Period: 2061 – 2090

Figure 23 provides an overview of the inputs and results associated with each of the Burn-P3 scenarios. Burn-P3 was also used to derive the percent increase in the area burned per year for both the baseline and 2050 scenarios for different fuel types. These results were used as inputs in the landscape projection modelling.

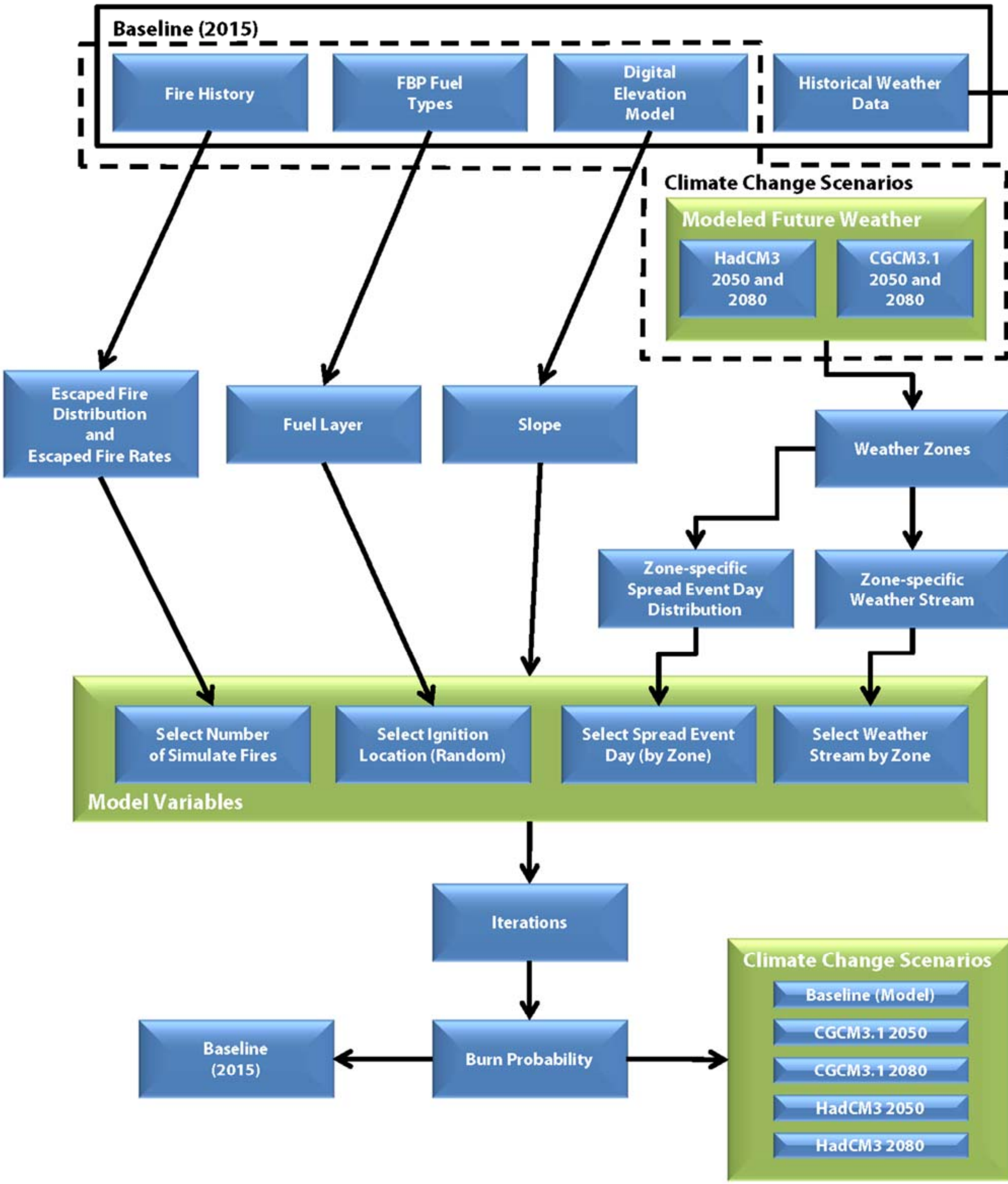
2.2.1 Baseline (2015) Scenario

The Baseline (2015) scenario represents current conditions (as of the fall of 2015). The parameters used for this scenario were:

Parameters

1. Fuels layer – Fire Behaviour Prediction (FBP) system fuel types obtained from the CFS were reclassified to account for recent (<= 10 years) fire activity on the landscape. Areas of fire activity < 5 years old were classified as 'non-fuel' and areas of fire activity > 5 years and <= 10 years old were re-classified as a mixed-wood fuel type with a 25% conifer component (Figure 24). This step ensured the dataset reflected conditions up to the end of the 2015 fire season. Each fuel type has a characteristic fire behaviour that varies based on weather and topography (Parisien et al., 2014).
2. Elevation – The Canadian Digital Elevation Data were resampled to a 250 metre cell size for use in the analysis. The elevation dataset (Figure 16) was used to derive slope values (Figure 17). Slope is used in the model because topography modifies fire behaviour by vectoring the wind speed as a function of slope (Parisien, 2014).
3. Weather zones – The weather zones (which equate to fire zones) are areas with distinct weather characteristics relative to fire conditions (see Section 2.1.5). Simulated fire growth is specific to each of these zones.
4. Fire Spread Event Days - A fire spread-event day is any day when the daily Fire Weather Index (FWI) value equals or exceeds 19. This limit of 19 was established based on research published in Podur and Wotton (2011). Since every actual fire on the landscape has the potential to burn on multiple spread event days, a spread event day distribution is established for the study area based on the historical weather records. Burn-P3 then uses this spread event day distribution to randomly select the number of spread event days for every simulated fire.

Figure 23. Overview of the Burn-P3 Modelling Process



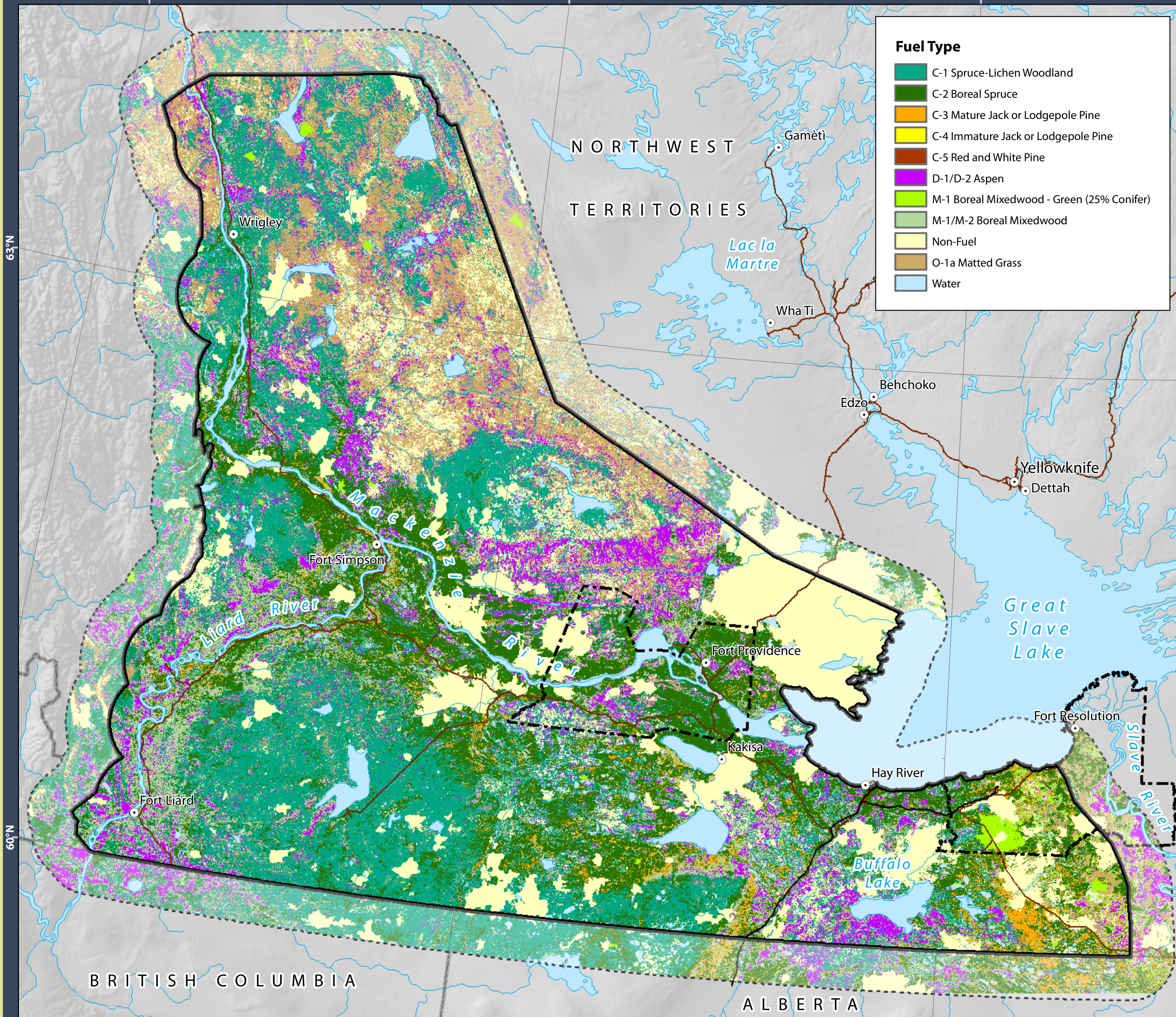


Figure 24

Baseline (2015) Scenario
Fuel Types

Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Ember Research Services Ltd

Prepared for: By:

Northwest Territories

CASLYS CONSULTING

March 2016

1. Escaped Fire Distribution - Every year the number of actual fires that occur within the study area will vary depending on a number of factors such as weather conditions and potential ignition sources (such as frequency and intensity of lightning events). Weather zone specific escaped fire distributions were determined by analyzing the fire history database for each of the weather zones defined for the study area. Burn-P3 then randomly samples from this distribution to determine how many simulated fires to generate for each iteration (year) of the simulation.
2. Ignition Sources and Locations – Burn-P3 allows the user to specify ignition sources (e.g., lightning- and/or human-caused fires) and where the ignition locations will occur. Random lightning fire locations were used to simulate fire ignitions on the study area landscape.

2.2.2 Baseline (Model) Scenario

The modelled baseline scenario was generated as a baseline for all of the climate change scenarios because it is not possible to directly compare the future climate change scenarios back to the Baseline (2015) scenario. This Baseline (Model) scenario differs from the Baseline (2015) scenario in that the fuel types from recent (<10 year old) fires were not re-classified as non-fuel or mixed-wood. Also, the Baseline (Model) scenario was generated from data derived from the modelled results to be compatible with the climate change models thereby facilitating an assessment of relative change.

2.2.3 CGCM3.1 Climate Change Models

Burn probability analyses were conducted for two climate change scenarios based on the CGCM3.1 climate change model: a scenario representing conditions from 2031 to 2060 (referred to as the CGCM3.1 2050 scenario); and a second one projected further out in time for the 2061 to 2090 time period (referred to as the CGCM3.1 2080 scenario). They vary from the Baseline (Model) in that fire weather conditions have been projected into the future based on daily weather for 18 weather stations summarized into four weather zones.

Parameter changes from the Baseline (2015)

1. Fuels layer – Unlike the approach used to generate the Baseline (2015) results, the fuels map[4] used for the climate change scenarios ignored recent fire history and used the original pre-burn fuel types. The pre-burn fuel types were used because fuel types following the recent fires would have been difficult to predict due to the confounded effects of climate change on future fuel types. Therefore, it would have been impossible to distinguish between changes in fuel due to actual changes in fuel, or due to changes in fuel type resulting from climate change. Also, the purpose of running climate change scenarios in Burn-P3 is to determine the potential relative differences between the different climate change models and time periods, and not to attempt to model the absolute differences in burn probability in response to potential changes in climate, so the absolute values in the Baseline (Model) scenario are not needed.
2. Weather data - The future fire weather data for use in the Burn-P3 climate change scenario analyses were obtained from the University of Alberta wildland fire group. These data were produced with the delta approach (Flannigan et al., 2005), which uses monthly data from the Intergovernmental Panel on Climate Change (IPCC) GCMs for future time periods and past time periods. The back cast period is subtracted from a future time period for all climate variables, and a monthly anomaly is generated. This monthly anomaly is then added to observed daily fire weather for every point of interest. This method follows the same approach described by Wang et al. (2015). In the end, the method resulted in future

[4] The FBP System fuel type data was derived from vegetation inventory data that was derived from remote sensing imagery and other ancillary data layers from the early 2000s.

daily fire weather observations for 18 locations in four weather zones for four time periods: 2001-2030 (2020s), 2031-2060 (2050s), and 2061-2090 (2080s).

3. Application of the CGCM3.1 model – The resulting burn probability maps for the CGCM3.1 2050 and 2080 Burn-P3 analysis were used as climate change input layers into the SELES landscape projection model.

2.2.4 HadCM3 Climate Change Models

Burn probability analyses were conducted for the same two time periods (i.e., scenarios) based on the HadCM3 climate change model: a scenario representing conditions from 2031 to 2060 (referred to as the HadCM3 2050 scenario); and a second one project further out in time for the 2061 to 2090 time period (referred to as the HadCM3 2080 scenario). They vary from the Baseline (Model) in that fire weather conditions have been projected into the future based on daily weather for 18 weather stations summarized into four weather zones.

Parameter changes from the Baseline (2015)

1. Fuels layer – The changes to the fuels layer were the same as those applied to the CGCM3.1 model (see Section 2.2.3).
2. Weather data – The changes to the weather data were the same as those applied to the CGCM3.1 model (see Section 2.2.3).
3. Application of the HadCM3 model – The resulting burn probability maps for the HadCM3 2050 and 2080 Burn-P3 analysis were then used as input layers into the SELES landscape projection model.

2.2.5 Burn Probability Model Calibration

Subsequent to the assembly and development of a Burn-P3 project file containing the various input layers, a series of ‘calibration’ runs were generated to calibrate the Burn-P3 model. A properly calibrated model will have a distribution of Burn-P3 generated fire sizes that are similar to the historical fire size distribution. Once calibrated, the model was run to simulate a large number of fires on the study area landscape. In this case, over 70,000 iterations were run using the Baseline (2015) scenario inputs and approximately 40,000 for each of the five (Baseline (Model), CGCM3.1 2050, CGCM3.1 2080, HadCM3 2050, HadCM3 2080) climate change scenarios. These large numbers of iterations are run to improve the level of confidence that can be placed in the results. The burn probability results generated by the model represent the average of all the iterations associated with a given scenario.

2.3 Landscape Model Development

The caribou range disturbance model examines the interaction of fire and anthropogenic disturbance, recovery and climate-change within the study area. The model reports statistics related to variables of management interest over a 100-year simulation period. Variables reported include undisturbed caribou range, patch size distribution, area harvested and developed roads. The model consists of six main modules: 1) fire, 2) vegetation and fuel recovery, 3) future road network, 4) timber harvesting, 5) seismic line recovery and 6) caribou range statistics.

2.3.1 Software

The simulation was developed in the Spatially Explicit Landscape Event Simulator (SELES) software. It is specifically designed to facilitate development of landscape-scale disturbance simulations (Fall and Fall, 2001). In SELES, the landscape is represented by a set of raster map layers (250 metre square raster cells); events are simulated every year, with reporting by decade. SELES does not pre-define ecosystem processes, allowing a wide range of models to be developed.

The modules use coding approaches from a recently developed cumulative effects assessment toolkit (Fall and Morgan, 2013) and from a similar assessment (Steventon and Daust, 2007 and 2009). Code was designed specifically to address the policy questions driving this project.

2.3.2 Map Layers

A set of map layers describes the study area and provides the initial conditions for the simulation. Map layers and global variables transfer information among SELES modules. Table 5 details the layers used to define initial conditions for the simulation. Two map layers created specifically for the simulation were more complicated to derive and are discussed below.

Table 5. Map Layers used in Landscape Simulation

Map Layer Description (file name)	Notes
Forest age in 2011 (Age_2011)	Composite of nt_forcov_origin, Age_Dehcho, Age_SouthSlave, fire_history_nwt_master_fireyear. Locations without forest age or time since fire data were set to an age of 200 years.
Forest strata (AU_Dehcho_SouthSlave)	Composite of AU_Dehcho and AU_SouthSlave; analysis units linked to yield curves
Percent aspen in stand (RecoveredAspen)	Aspen distribution derived from recovered fuel group
Burn probability for climax fuels (ClimaxFireProb)	Composite of fire probabilities for C2 and adjusted M1 fuels (from maps fire_prob_c2_10, fire_prob_M125C_10, NWT_2016_Baseline_Model _BPpct_10); see methods below
Recovered fuel types (RecoveredFuel)	Derived from land cover imagery and Fuel_orig (circa 2011); see methods below
Grouped recovered fuel types (RecoveredFuelGroup)	
Linear disturbance features (EC_DisturbLine)	Linear disturbances (e.g., roads, seismic, powerlines from ec_borealdisturbance_linear_2008_2010)
Areal disturbance features (EC_DisturbPoly)	Polygonal disturbances (e.g., mines, settlement, gas wells from ec_borealdisturbance_polygonal_2008_2010)
Land cover (eosd_land_cover_DD)	From imagery
Year of last fire (FireYear_DD)	From fire_history_nwt_master_fireyear
Current fuel type (fuel_2015_DD)	Same as used in Burn P3
Burn probability for CGCM3.1 in 2050 (NWT_2015_CGCM_2050_BPpct_10)	Results from Burn P3
Burn probability for CGCM3.1 in 2080 (NWT_2015_CGCM_2080_BPpct_10)	Results from Burn P3
Burn probability for HadCM3 in 2050 (NWT_2015_HAD_2050_BPpct_10)	Results from Burn P3
Burn probability for HadCM3 in 2080 (NWT_2015_HAD_2080_BPpct_10)	Results from Burn P3
Burn probability for historical climate (NWT_2016_Baseline_Model_BPpct_10)	Results from Burn P3
Operating areas for harvest access (OpArea_FtProv_FtRes_Revised	Combined Fort Providence operating areas and Fort Resolution buffers
Study area (study_area)	
Study area with 25 km buffer (study_area_25km_buffer)	
Timber harvesting landbase (THLB_95)	Forest strata within the timber harvest planning areas
Timber harvest planning areas (timber_harvest_planning_areas)	Also called management units in the model

2.3.2.1 Recovered Fuel Map

To simulate recovery from fire, currently-described non-fuel and open fuel types need to be assigned to a potential 'recovered' fuel type. To estimate recovered fuels we began with an earlier version of the fuels map that excluded 2014 and 2015 fires and hence showed more fuel coverage. Using this map, a correlation matrix between the EOSD land cover classes and fuel types was developed (Appendix C) for the portion of the landscape not recently burned. Using the EOSD land cover map and the correlation matrix, we projected recovered fuel types for the recently burned area. Unfortunately, because the correlation between the fuels and land cover layers was relatively poor, the projected recovered fuels map did not appear to be consistent with existing fuels. The correlation matrix was modified manually to better account for the fuel composition adjacent to burned areas and we projected recovered fuels again. Re-projected fuels fit better with the current fuel distribution, based on visual inspection. The re-projection increased the proportion of the C1 fuel type in the northeast portion of the study area.

2.3.2.2 Climax Burn Probability Map

The simulation uses a burn probability map to determine the rate of spread and size of fire that occurs within different regions of the study area. Burn probability is determined by topography, weather patterns and forest fuel types. To reflect the influence of fuel type succession on fire probability, a climax fire probability map is needed. The historical fire probability map is insufficient because it is based on deciduous and mixedwood fuel types that may shift to conifer and become more flammable over time. The climax burn probability map shows the burn probability if all deciduous and mixedwood stands were to transition to conifer and facilitates modelling of succession.

Creating a climax fire probability map (Figure 25) required several steps. First, two additional Burn-P3 fire simulations were run on modified versions of the Baseline (model) fuel maps (see Section 2.3.2), one map where existing deciduous and mixedwood fuels were recast as coniferous fuels and one where coniferous and deciduous fuels were recast as mixedwood fuels. The mixedwood fire probabilities were rescaled to mimic conifer probabilities based on area-burned ratios for different fuel types (Hély et al., 2000). The rescaled mixedwood and coniferous fire probability maps were examined for consistency and then merged to generate a climax fire probability map showing relative probability of fire if all fuel types are in their most flammable state. Areas with fuel codes but missing fire probabilities were filled with values from the nearby raster cells.

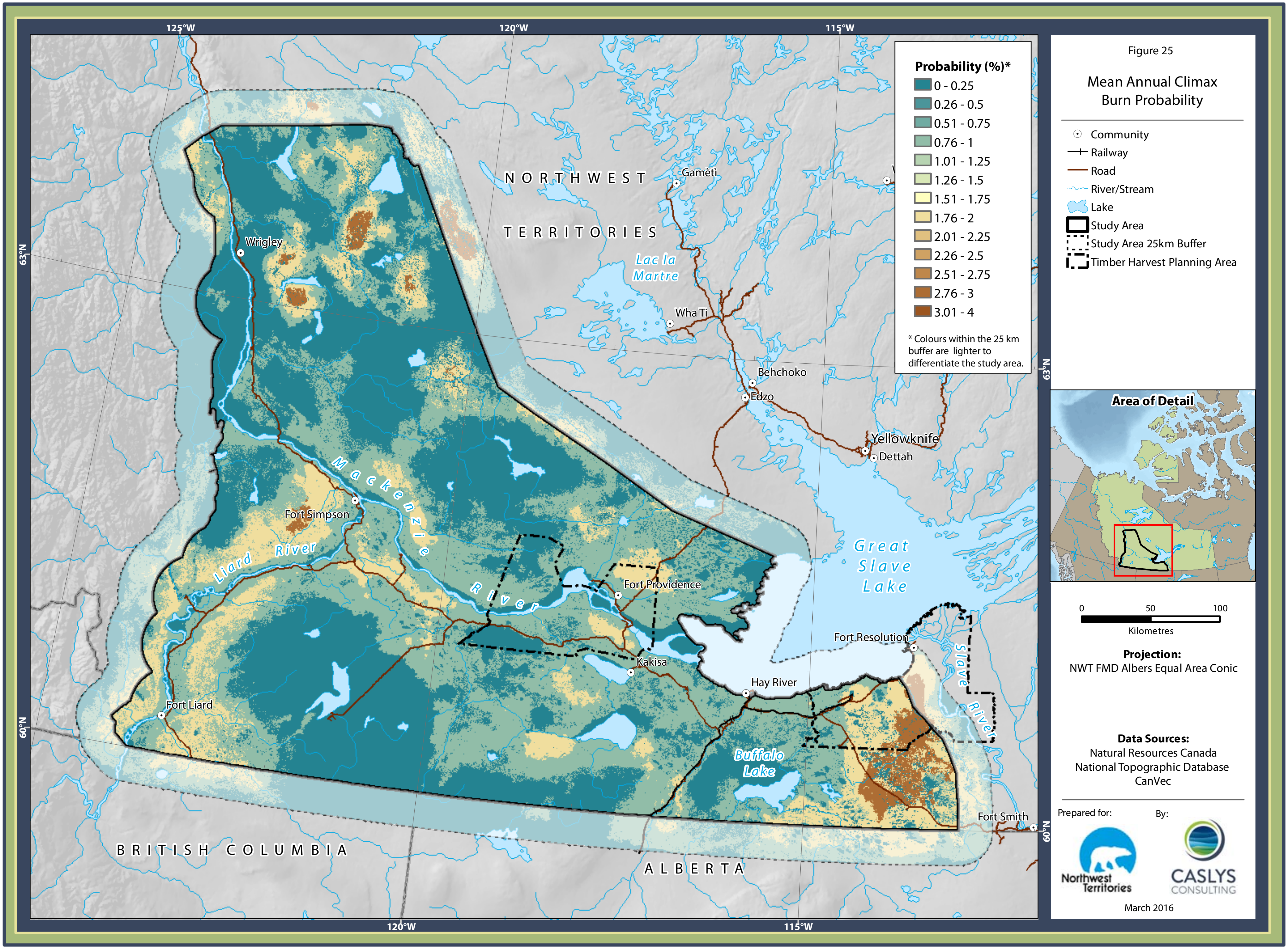


Figure 25
Mean Annual Climax Burn Probability
Probability (%)*
0 - 0.25
0.26 - 0.5
0.51 - 0.75
0.76 - 1
1.01 - 1.25
1.26 - 1.5
1.51 - 1.75
1.76 - 2
2.01 - 2.25
2.26 - 2.5
2.51 - 2.75
2.76 - 3
3.01 - 4
* Colours within the 25 km buffer are lighter to differentiate the study area.
Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Area of Detail
0 50 100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
125°W
120°W
115°W
63°N
60°N
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
Gamètì
Wrigley
Lac la Martre
Wha Ti
Behchoko
Edzo
Yellowknife
Dettah
Mackenzie River
Fort Simpson
Liard River
Fort Providence
Great Slave Lake
Fort Resolution
Kakisa
Hay River
Slave River
Fort Liard
Buffalo Lake
Fort Smith

2.3.3 Fire Module

The fire module simulates the ignition and spread of fires each year (Figure 26). It is driven by a list of target annual burn areas. We generated the list of targets from a negative exponential distribution based on historical mean area burned in the study area (Johnson and Gutsell, 1994). Between 1950 and 2015, annual area burned in the study area has varied by four orders of magnitude, from less than 100 hectares to more than 1,000,000 ha (Figure 27). To better capture variability in year-to-year disturbance, we calculated historical means for 'hot', 'moderate' and 'cool' years, where year type is defined by area burned, and created targets for different year types in proportion to their historical frequency (Table 6). Given a target annual burn, the fire module selects the number of fires appropriate for the annual area to burn. Years with more area burned tend to have more fires (Section 1.3.3.1). Mean fire size equals target annual burn area divided by the number of fires.

Figure 26. Overview of the Fire Module

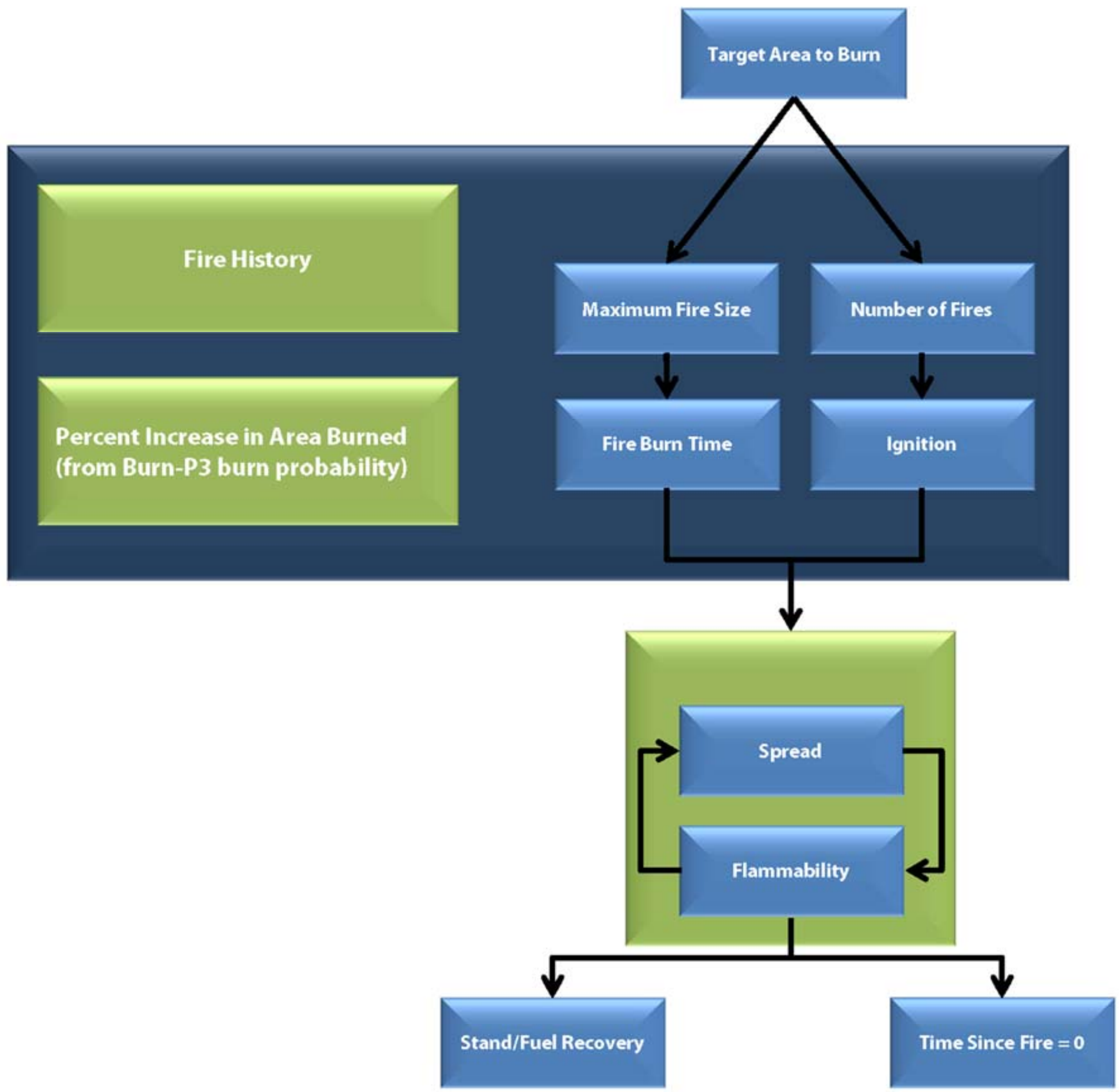
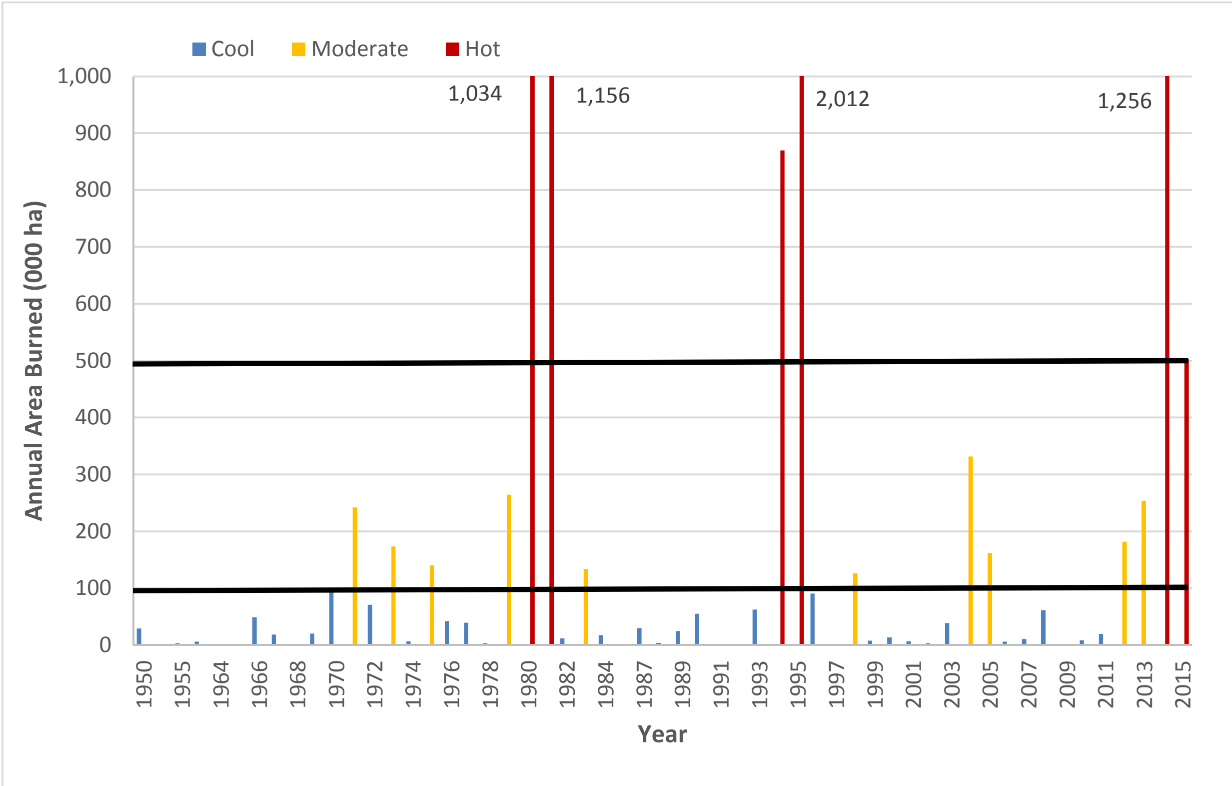


Figure 27. Annual Area Burned in the Study Area between 1950 and 2015



** Years are placed into classes of cool, moderate and hot based on the range of annual area burned, respectively 0 - 100,000 ha, 100,000 - 500,000 ha and 500,000 - ~2,000,000 ha.*

Table 6. Annual Burn Area and Proportion of Years in Different Year Classes

Year Class	Annual Burn Range (ha)	Mean Annual Burn (ha)	Percentage of Years
Hot	500,000 – ~2,000,000	1,139,000	11
Moderate	100,000 – 500,000	201,000	18
Cool	0 - 100,000	22,000	71

**Year class is defined by annual area burned range. Data are from Fire_History_NWT_Master.xls*

The fire module identifies the flammable portion of the study area (i.e., areas with non-zero burn probability) from a burn probability map, initially derived from Burn-P3 results (Section 2.3.3.1), and ignites fires within the flammable region, at random locations. As fires ignite, a target fire size is selected from an exponential distribution based on mean fire size. Based on the target fire size, the fire is assigned a maximum number of burn time units appropriate for the most flammable fuel type (Table 7). SELES uses burn time units which are based on historical fire size whereas the Burn-P3 analysis used spread event days which are based on historical weather data. Prior to conducting simulation experiments, burn time required calibration to better match target annual burn rates.

Table 7. Mean Flammability Across the Landscape of Different Fuel Types

Fuel Group	Fuel Types	Mean Flammability Score
Wetland Conifer	C1	0.5
Upland Conifer	C2, C3, C4, C5	1.1
Mixedwood	M1, M125C	0.8
Deciduous	D1	0.4
Open	O1	0.6

Fires burn in sequence. Each fire spreads from the ignition cell to adjacent flammable cells and then the spread process is repeated, generating a spreading patch of fire. The time required for adjacent cells to burn depends on their probability of burning relative to the maximum, that is, relative time to burn is the inverse of relative burn probability (pBurn /maximum pBurn). For example, cells with maximum flammability take one time unit to burn; cells with 50% of maximum flammability take two time units. The maximum number of burn time units assigned to the fire is decremented by the units used to burn the cell. The order in which cells are burned also reflects the time units used, thus slowing spread in less flammable fuels.

2.3.3.1 Burn Probability Map

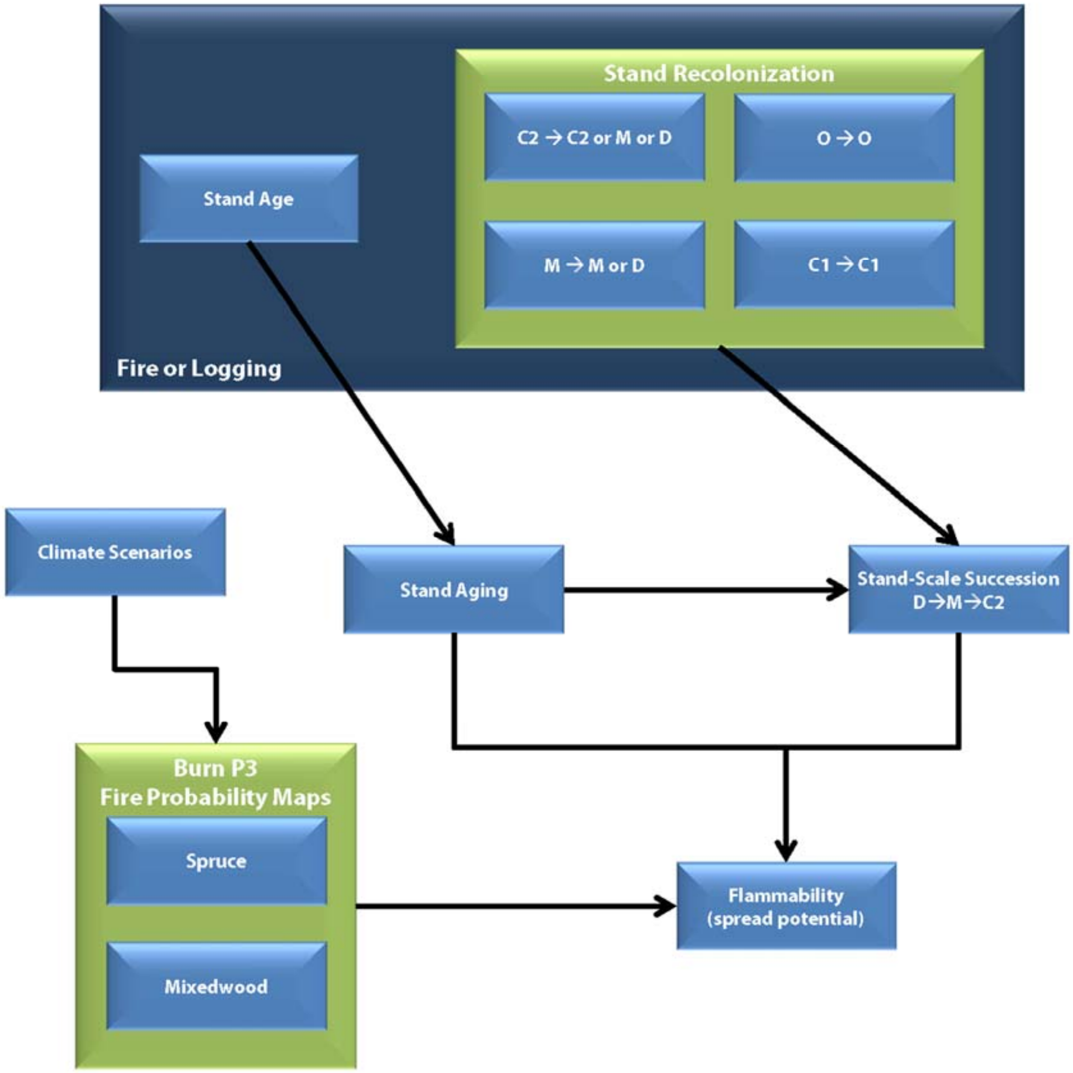
The fire module uses a burn probability map to determine the relative rate of fire spread across different portions of the landscape. Burn probability maps influence fire spread rates in different portions of the landscape, and influence total area burned in conjunction with annual burn targets. The burn probability map used in the fire module is based on the climax fire probability map (described above in Section 2.3.2.2). During simulation, the map is adjusted to account for mid-successional fuel types and for a fuel recovery period (discussed below). Deciduous and mixedwood fuel types reduce climax burn probability to 10% and 44% of maximum values respectively, based on relative burn rates described in Hély et al. (2000).

To simulate climate change, baseline-climate burn probability maps were subtracted from projected-climate burn probability maps (Table 6) to determine the percentage increase or decrease in burn probability over time in each raster cell. The hot and relatively dry HadCM3 model projects increased fires whereas the hot, but wetter, CGCM3.1 projects a small decrease in fires.

2.3.4 Fuel Recovery Module

The fuel recovery module simulates changes in fuel types (Section 2.1.2.3) following fire. It can simulate simple recovery to the pre-disturbance fuel type or it can simulate more complex fuel recovery that depends on successional changes in the relative abundance of deciduous and coniferous species. The fuel recovery module also modifies the burn probability map to reflect changes in flammability associated with fuel recovery and succession. For example, a 25-year old conifer stand has 50% of climax burn probability (see Section 2.3.4.1); similarly a pre-disturbance spruce stand that regenerates to mixedwood has 44% of climax burn probability (see Section 2.3.4.2). The recovery simulation relies on a recovered fuel map that shows the fuel types that disturbed areas will recover to. Figure 28 provides an overview of the module's inputs and outputs.

Figure 28. Overview of the Fuel Recovery Module



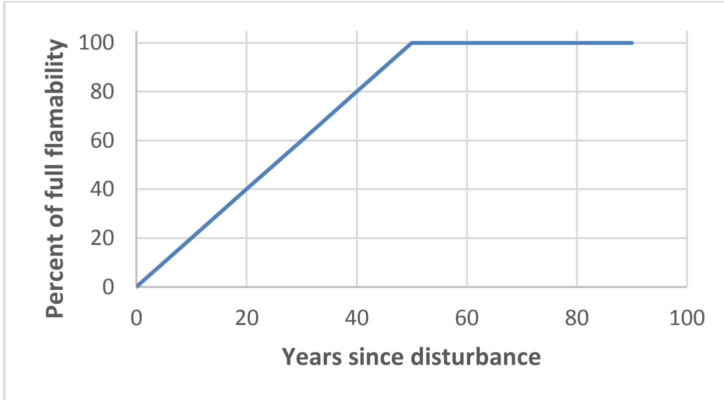
2.3.4.1 <u>Simple Fuel Recovery</u>

The simple version of the fuel recovery module assumes that post-disturbance stands largely resemble pre-disturbance stands in species composition following a recovery period of 50 years (Table 8). In the simulation, flammability of recovering stands is calculated as percent recovery, based on 2% recovery per year (Figure 29), times the flammability of the pre-disturbance stand as described by the burn probability map.

Table 8. Simple Fuel Recovery Model

Pre-disturbance	Recovery Phase (50 years)	Recovered
C1 (woodland spruce) →	Non-Fuel →	C1
C2 (boreal spruce) →	Non-Fuel →	C2
D1 (deciduous) →	Non-Fuel →	D1
M1 (mixedwood) →	Non-Fuel →	M1
O1 (Open) →	Non-Fuel →	O1

Figure 29. Recovery of Flammability Versus Time Since Disturbance



A modification of the simple fuel recovery model applies a regeneration lag to stands following disturbance (Table 9) and assumes a 25 year flammability recovery period. The 25 year recovery aims to capture canopy closure. This modification is compared to the simple 50 year recovery.

Table 9. Percentage of Sites with Specified Regeneration Lag*

Regeneration Lag (years)	10	20	30	40	50
Percentage of Sites	1	30	15	40	14

**Lag estimates provided by GNWT, based on sample plots.*

2.3.4.2 <u>Complex Fuel Recovery with Succession</u>

The fuel recovery module also simulates a more complex fuel recovery pathway, accounting for variable recolonization and succession processes that lead to shifts in stand composition and fuel flammability over time (Table 10). The model distinguishes boreal forest from woodland forest from open sites. Boreal sites include areas with well-stocked conifer (C2, C3, C4, C5), mixedwood (M1) or deciduous (D1) fuels. Woodland sites have conifer (C1) fuels. Open sites have open (O1) fuels.

Table 10. Potential Succession Pathways for Different Forest Types and Different Pre-disturbance Fuel Types*

Forest Type	Pre-disturbance Fuel*	Fuel Succession Pathway					
Upland and Lowland Boreal	C2	→	D1	→	M1	→	C2
		→			M1	→	C2
		→					C2
	C3-4	→			M1	→	C3-4
	M1	→	D1	→	M1	→	C2-4
		→			M1	→	C2-4
	D1	→	D1	→	M1	→	C2
Woodland	C1	→					C1
O1	O1	→					O1

**C1= woodland spruce; C2 = boreal spruce; C3-5 = pine; D1 = deciduous; M1 = mixed spruce-aspen; O1 = open*

The recovery module simulates recolonization following disturbance and species succession over time. Recolonization increases the proportion of deciduous-leading and mixedwood stands relative to conifer stands in the boreal forest type, depending on pre-disturbance fuel type (Table 11).

Table 11. Probability of Post-disturbance Colonization to a Fuel Type as a Function of Pre-disturbance Fuel Type

Forest Type	Pre-disturbance Fuel	Post-disturbance Fuel			
		Conifer	Conifer-Deciduous	Deciduous	Open
Boreal	Conifer (C2) Spruce	0.20	0.40	0.40	0.00
	Conifer (C3-4) Pine	0.90	0.10	0.00	0.00
	Mixedwood (M1)	0.00	0.50	0.50	0.00
	Deciduous (D1)	0.00	0.00	1.00	0.00
Woodland	Woodland Conifer (C1)	1.00	0.00	0.00	0.00
Open	Open(O1)	0.00	0.00	0.00	1.00

As part of the recolonization process the module assigns a percent deciduous component to each post-disturbance stand type, randomly within the range appropriate to the stand type (Table 12). The recovery module then simulates decline of deciduous species over time, as a function of forest type and deciduous abundance (Table 13). Mixedwood stands shift more rapidly towards increased conifer composition than do deciduous stands (Figure 30) affecting species composition on the landscape (Figure 31). Decline of deciduous species aims to capture variable rates of growth and mortality among coniferous and deciduous species and possible infill of shade-tolerant conifer species. During simulation, deciduous abundance is used to determine changes in fuel types (Table 13). Changes in fuel types are then translated to changes in burn probability by multiplying climax burn probability by the relative flammability of the fuel type (Table 14). For example, a 50-year old mixedwood stand will have 44% of the flammability of a conifer stand in the same location; flammability affects fire spread rate and size. The two percent per year fuel recovery factor (from age 0 to 50), described for the simple fuel recovery model is also applied here, following succession. Thus, burn probability reflects the effects of changes in both the species composition and age of the stand.

Table 12. Range of Percentage of Deciduous and Coniferous Species Composition Assigned to Different Fuel Types

Fuel Type	Deciduous (%)	Coniferous (%)
Conifer (C2 – C5[5])	0 to 25	75 to 100
Mixedwood (M1, M1-25C)	25 to 75	25 to 75
Deciduous (D1)	75 to 100	0 to 25

Table 13. Yearly Decline in Proportion of Deciduous Species in Forested Fuel Types for Different Densities of Deciduous Species and Different Time Periods Following Disturbance

Time Since Disturbance	Boreal Forest	
	>75% deciduous	≤ 75% deciduous
0 - 25 years	0	0
> 25 years	0.004	0.015*

**A slower succession rate of 0.01 was tested in a sensitivity analysis.*

[5] While fuel type C5 (Red and white pine) is not typically a coniferous species present in the NWT, the algorithm that CFS uses to classify vegetation from remote sensing into the 16 different FBP System fuel types has classified 182 cells (1137.5 ha) in our study area plus buffer as C5. Apparently, the fire behaviour characteristics of the vegetation in these 182 cells is most likely to behave as a C5 fuel type even though the vegetation is probably not red or white pine. The CFS fuel type algorithm was developed by scientists at the CFS in collaboration with fire specialists in the various provincial and territorial governments (personal communication with Marc Parisien, July 2016).

Figure 30. Rate of Decline of Deciduous Component in Mixedwood and Deciduous-leading Stands

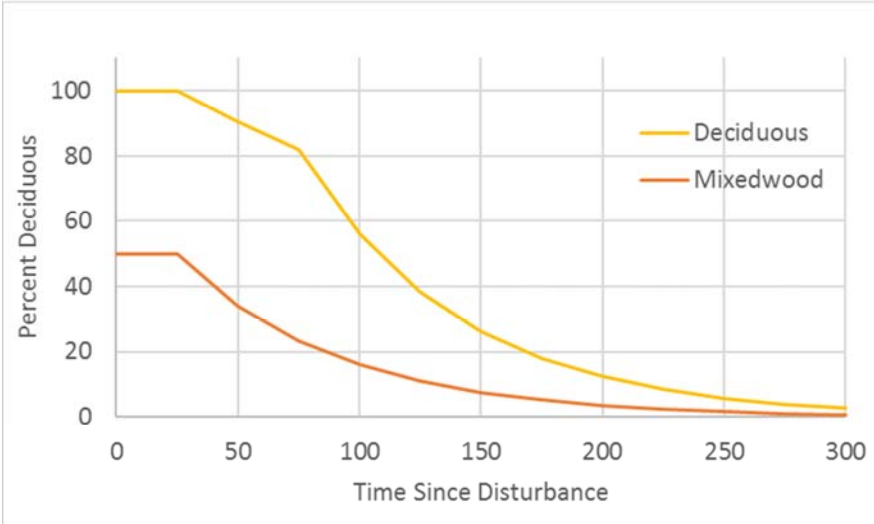
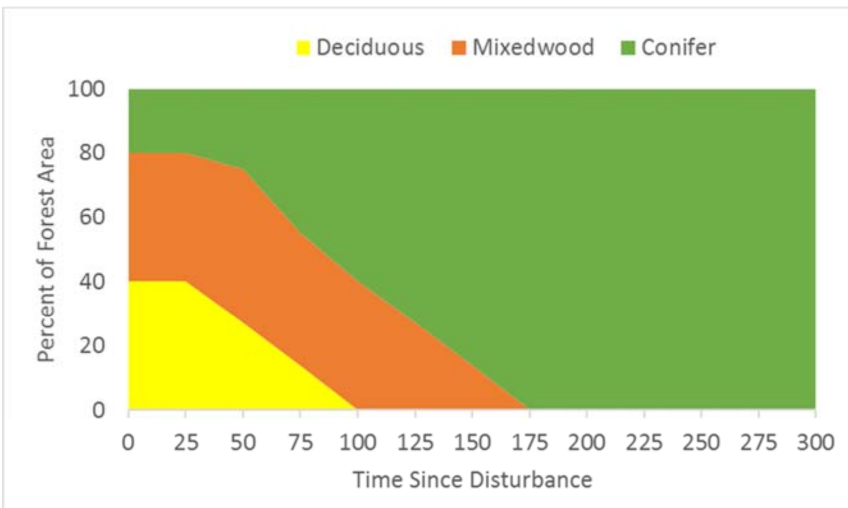


Figure 31. Proportion of Deciduous, Mixedwood and Conifer Stands on a Landscape versus Time



Assumes an initial landscape composition of 40% deciduous, 40% mixedwood and 20% conifer. Successional change in stand types over time reflects loss of deciduous species within stands (Figure 30).

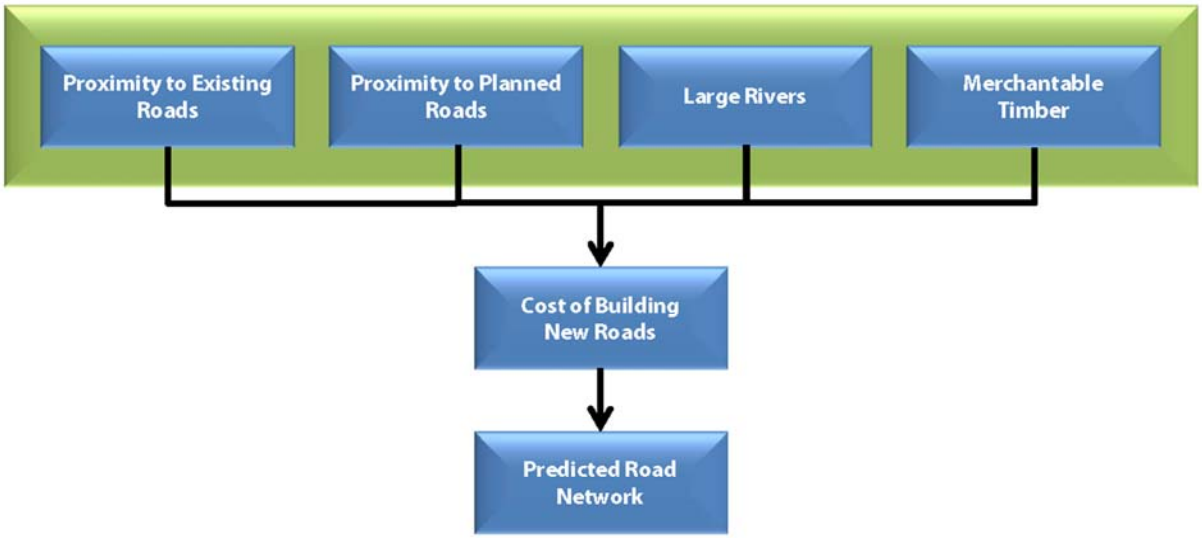
Table 14. Percent of Maximum Burn Probability For Successional Fuel Types

Fuel Type	Percent of Maximum Burn Probability
Conifer (C2 – C5)	100%
Mixedwood (M1, M1-25C)	44%
Deciduous (D1)	10%

2.3.5 Future Road Network Module

The road network module (Figure 32) predefines a realistic road network for areas to be developed for timber harvesting in the study area. Road access is required for forest harvest; other development activities are not considered. During the forest harvesting simulation, road segments are 'built' as needed to access cutblocks.

Figure 32. Overview of the Future Road Network Module



The road network module requires several map layers (Table 15). It consists of three sub-modules: one to create an access cost surface; one to generate a feasible road network; and one to summarize the road network as a series of road segments.

Table 15. Map Layers Used to Create the Future Road Network

Map Layer	Source Map
Buffered study area	study_area_25km_buffer
Area to access: identifies the area in which to plan road access.	Timber_harvest_planning_areas
Existing roads	tr_road
Planned roads	ftprov_thpaccess_roadtype; ftres_thpaccess_roadtype
Access cost: a surface with relative costs for constructing a road	Output from Access Cost sub-module
Mackenzie River	Created from ftprov_compartments
Road exits: identifies locations of 'road exits' from the buffered study area.	Generated

2.3.5.1 Access Cost Sub-Module

The access cost sub-module, adapted from Fall and Morgan (2013), calculates the relative cost per kilometre of building a road across each raster cell in the study area. Cost factors are based on biophysical features and management zones (Table 16). In the study area, higher costs are associated with the Mackenzie River. Lower costs are associated with stands that have merchantable timber. Very low costs apply to already-planned road locations. Costs were calibrated to generate plausible road development patterns: one crossing of the McKenzie River; a strong preference for already-planned routes; and a moderate preference for routes that pass through merchantable timber (i.e., 11/29 of the cost of passing through non-merchantable timber).

Table 16. Cost Factors Affecting Road Location

Cost Factor	Relative Cost
Existing roads	1
Planned roads	1 to 2
Merchantable stands	11
Non-merchantable stands	29
Mackenzie River	43

2.3.5.2 Road Network Projection Sub-Module

The road network projection sub-module creates a network of routes that can provide access to all portions of the Fort Providence and Fort Resolution FMAs. Only a portion of these routes are needed to harvest timber during simulation. The road network projection sub-module begins by identifying and removing areas unsuitable for road construction (e.g., steep terrain) and areas with access restrictions (e.g., parks and protected areas) where applicable. It then creates a road network based on factors affecting construction cost, for example, by using existing roads where possible and avoiding the Mackenzie River (see Fall and Morgan (2013) for additional detail). Figure 33 depicts an example of a network of future road options for the Fort Providence area based on the cost factors prescribed by the model. It should be noted that the network represents the optimum locations for all roads throughout the area however, only those roads leading to proposed harvest blocks would be constructed. The model used stands within the Dehcho and South Slave landbases that had yield curves. These stands appeared to omit areas in conservation zones.

2.3.5.3 Road Segment Sub-Module

The road segment sub-module divides projected raster roads into segments, between junctions, that are then used in the harvesting module. The harvesting model identifies road segments needed to access harvest units. While different simulations will use different roads in different time periods, the location of roads is fixed and hence road location does not act as a spurious source of variation in simulation results. As appropriate, sensitivity analysis can be conducted on road locations.

2.3.6 Timber Harvesting Module

To be eligible for harvesting, a stand must match criteria described in timber supply analyses for each FMA, such as minimum harvest age and 'open' operating area. Eligible stands are then selected based on several management goals including stand age (e.g., oldest first), proximity to roads and proximity to other cutblocks (Figure 34). The timber harvesting module simulates the size and location of cutblocks for each time step, based in part on data and assumptions used in the existing spatial harvesting predictions developed for the Fort Providence and Fort Resolution FMAs. Each year, the harvesting module attempts to harvest a specified target area in each FMA (Table 17). The targets are based on the timber supply analyses for each FMA. Data limitations prevented use of volume-based targets, however, the model is designed to use either area or volume as a target. The module selects stands to harvest in each time step based on eligibility and preference. Patterns of cutblock development appear to match existing spatial timber supply projections for the FMAs. The harvesting module has the capability to simulate salvage harvesting, when volume-based harvest targets are specified.

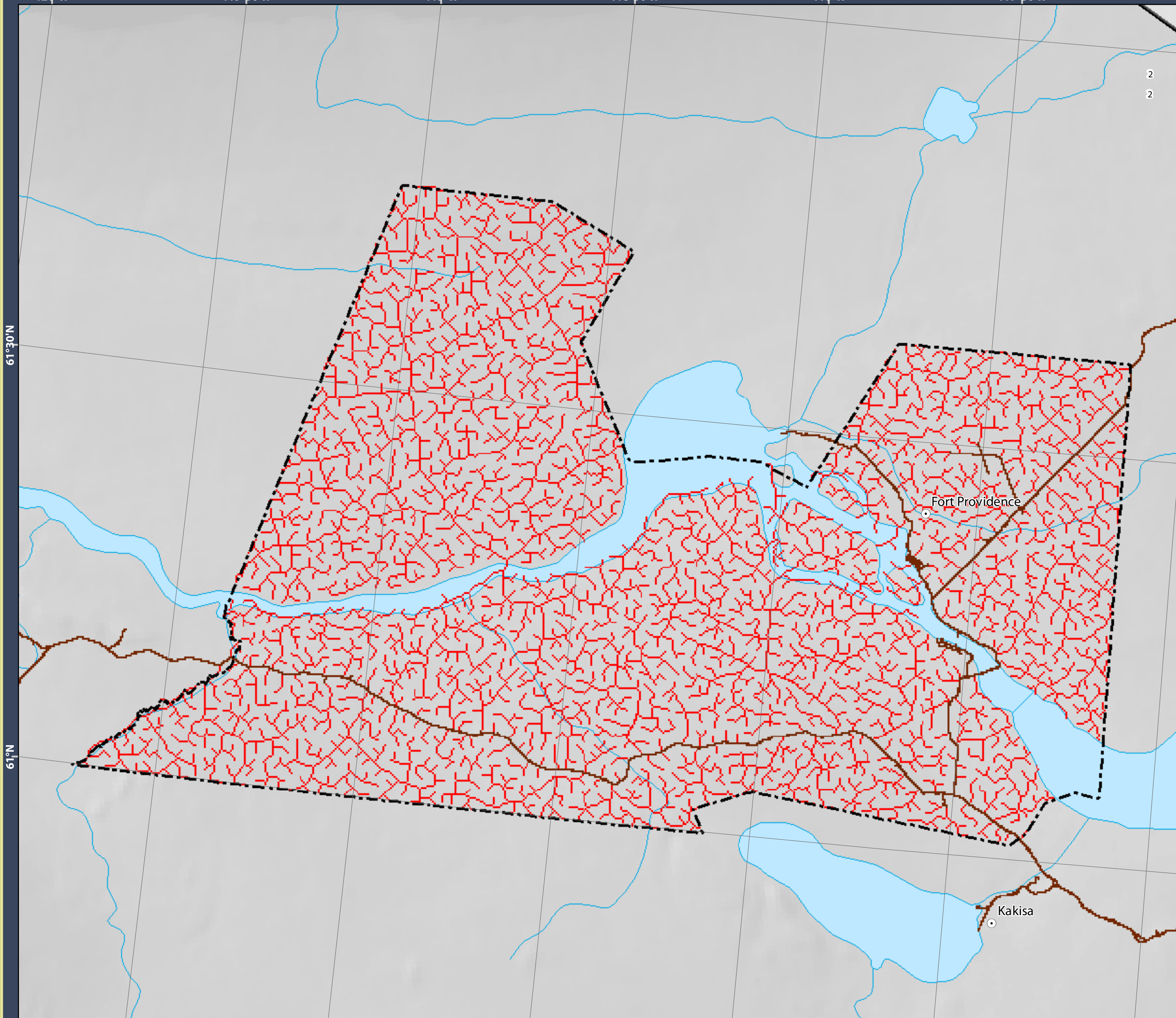


Figure 33

Example Future Road Options for Fort Providence

Community
River/Stream
Lake
Timber Harvest Planning Area

Roads

Existing (2015)
Future

* Colours within the 25 km buffer are lighter to differentiate the study area.

0 10 20
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

Figure 34. Overview of the Timber Harvest Module

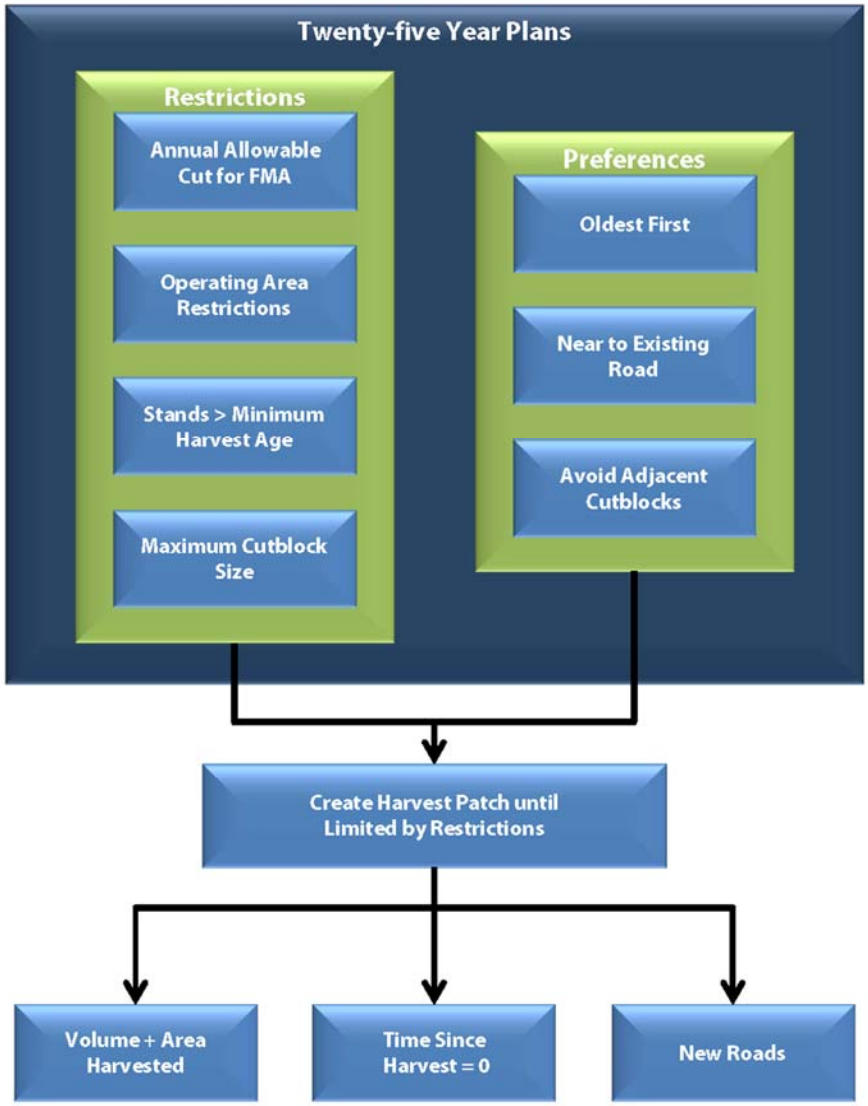


Table 17. Harvest Target Area for Fort Providence and Fort Resolution

	Harvest Area Target (hectares)	
Interval (years, beginning 2016)	**Fort Providence**	**Fort Resolution***
0 – 10	1089	600
11 – 50	1161	600
51 – 200	1161	647

**Harvest target reduced to account for proportion of harvesting land base within buffered study area.*

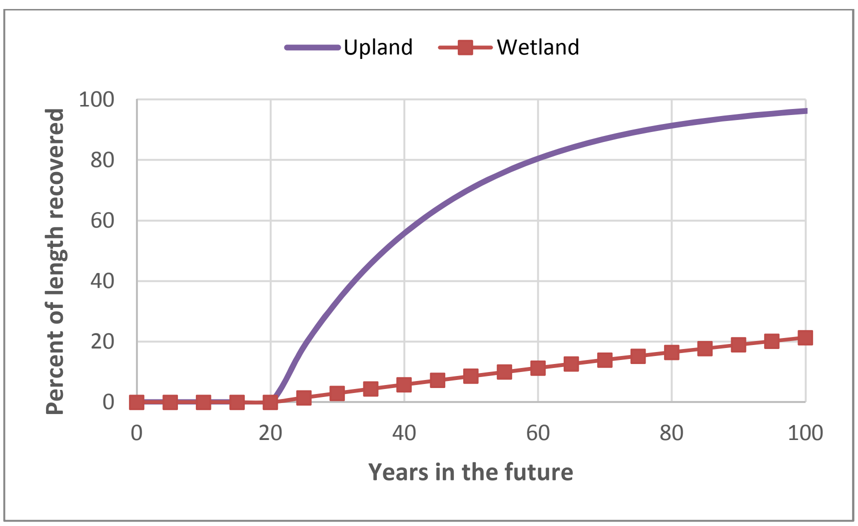
Harvesting disturbance interacts with other modules by altering stand age and vegetation type. These variables are used to determine suitability of stands for boreal caribou habitat and the flammability of the stand, as well as future timber harvesting potential. The harvesting model also 'builds' road linkages needed to access harvested units; these linkages then become part of the active road network influencing caribou habitat and future harvesting preference.

Following harvesting, stand aging and succession is modelled using the fuel recovery module. Then a growing stock model determines the total volume of merchantable timber within each FMA (not reported due to lack of volume-based information). Disturbance and recovery processes are simulated in yearly time steps. Each year begins with winter timber harvest and related road construction. Stand age is set to zero by harvesting, reducing the flammability of the site. Fire occurs during the spring/summer months. In the fall, the model increments stand age by one year and simulates fuel succession. It adjusts burn probability to reflect succession and climate change. The simulation then moves to the next year and repeats the process. During sample years, the model calculates boreal caribou range condition following fire disturbance and before stand ageing.

2.3.7 Seismic Line Recovery Module

The seismic line recovery module simulates the recovery of seismic lines (Figure 35). As seismic lines age, they have a probability of recovering to an undisturbed state. The probability varies with land cover type. Wetland cover types (wetland treed, wetland shrub and wetland herb in the EOSD land cover map) recover more slowly than upland types (defined as not wetland on EOSD). Wetland covers 18% of the study area but only 12% percent of seismic line length occurs on wetland sites. Seismic line recovery was applied at the scale of the raster cell (250 m length), reflecting the assumption that variability in site conditions at this scale influences recovery as much or more than construction techniques. Note that since most pipelines were built more than two decades ago, the seismic line recovery module assumed that the first 20 years of recovery (Figure 35) was complete at the start of the simulation.

Figure 35. Projected Recovery of Seismic Lines to Undisturbed Condition versus Time



As a sensitivity analysis, we examined recovery of logging roads as an alternative to the baseline assumption of no road recovery. The logging road recovery algorithm used the same recovery curves as those for seismic lines (Figure 35). We also examined the effects of immediate recovery after forty years of no use, paralleling the cutblock recovery assumption.

2.3.8 Caribou Range Statistics Module

The range statistics module calculates the area and proportion of undisturbed caribou range in six patch size classes: 0 to 100 km^2, 100 to 200 km^2, 200 to 300 km^2, 300 to 400 km^2, 400 to 500 km^2 and > 500 km^2. First, the module combines permanent linear features (e.g., existing roads and power lines (Figure 21)) with new logging roads (see Section 2.3.6) and unrecovered seismic lines (see Section 2.3.7) and creates a 500 metre buffer around these features. It then combines permanent areal features (e.g., mines, settlement, gas wells (Figure 21) with unrecovered cutblocks (see Section 2.3.6) and creates a 500 metre buffer around these features. Buffered linear and areal features are then combined with recent (< 40 year old) fires (see Section 2.4) to create a disturbed and undisturbed caribou range layer. The module identifies patches of undisturbed range bounded by disturbed range and calculates the area in each patch-size class. Patches are created for the study area plus a 25-km extension, but only the area of each patch size class within the study area is tallied. This approach avoids creating artificially small patches along the study area boundary.

The 500 metre buffer around anthropogenic features and 40 year recovery time period for fires follow the Boreal Caribou Recovery Strategy (Environment Canada, 2012). Analyses supporting the strategy identified anthropogenic disturbances based on their visibility on satellite imagery. Thus no recovery period for cutblocks was specified. For our calculations, we assume cutblocks recover undisturbed status in the same time frame as fires: 40 years. Note that roads accessing cutblocks do not recover except in sensitivity analyses. To test the importance of recovery period, we increased recovery to 60 and then to 80 years, analogous to adding 20 and 40 year regeneration lags, consistent with current knowledge for NWT.

2.4 Simulation Experiments

Simulation experiments adjust a set of policy and natural-process variables (e.g., area harvested, area burned by wildfire) to determine the effects of different management policies under a range of plausible environmental conditions. Non-experimental variables (e.g., stand age eligible for timber harvest) remain fixed during simulation experiments.

Stochastic simulations, such as this one, need to be replicated to determine the mean and range of outcomes. Ten replicates were conducted for each experiment. Simulation experiments address the four main objectives:

1. Quantify the effect of fire and forest harvest disturbance on boreal caribou range (amount and distribution); undisturbed range is equivalent to undisturbed habitat in the Boreal Caribou Recovery Strategy.
2. Assess the effect of boreal caribou range targets/constraints on timber supply given fire disturbance.
3. Evaluate the effect of linear feature recovery on caribou range in the context of disturbance.
4. Determine the potential for timber harvesting to mitigate fire disturbance and maintain caribou range.

Simulation experiments use different plausible assumptions about fire disturbance and fuel recovery, climate change, timber harvesting and vegetation recovery (Table 18) to examine potential future outcomes for boreal caribou range and timber supply. Fire, forest harvest and vegetation recovery interact to influence boreal caribou range. Harvesting preferences and fuel recovery rates also influence fire dynamics.

Table 18. Fire and Harvesting Scenarios

Fire Disturbance		Timber Harvesting	Seismic Recovery	Caribou Range Recovery
Annual Burn	Vegetation and Fuel Recovery			
• No fire • **Annual burn rate based on historical climate** • **Annual burn rate based on CGCM3.1** • **Annual burn rate based on HadCM3**	• Immediate* • **Simple: 50 year recovery** • Simple: Regeneration lag + 25 year recovery • Complex: Succession • **Complex: Succession + 50 year recovery**	• **No harvest** • **Green-tree harvest based on FMA timber supply analysis and planned spatial harvest pattern**	• **Standard**	• **40 years** • 60 years • 80 years

**This scenario recovers the fuel type immediately after disturbance; although unrealistic, it bounds the results using the most rapid fuel recovery time possible.*

Two sets of simulation experiments were conducted. The first tested the influence of a wide range of individual parameters (Table 18) on caribou range to determine their relative influence. This process identified some less important parameters and some parameter combinations that produced very similar results. The second set of simulations examined the cumulative effects of the most plausible future scenarios using parameters identified as important in the first set of simulations (identified by the bold text in Table 18). Where parameter combinations were similar, the simpler approach was chosen.

2.5 Restoration Status

Caribou habitat assessment define anthropogenic disturbance based on the visibility of features on satellite images. In order to estimate disturbance recovery period, needed for projecting future disturbance levels, we examined the influence of seismic line origin dates on their visibility. We compared visible seismic lines on the Environment Canada (EC) anthropogenic disturbance dataset with seismic line dates recorded by the National Energy Board (NEB).

The EC disturbance dataset was generated by digitizing visible features using Landsat imagery from 2008-2010, therefore it contains features thought to be active disturbances on the landscape as of 2010. However, the dataset does not contain temporal information that could be considered in restoration analysis. To gain information about feature dates, the EC linear disturbance dataset was compared with the NEB seismic lines, which contains information about the start and end dates of the seismic program. Using a selection query in ArcGIS, the EC lines were tagged with the end date of the nearest the NEB line using a 50 metre search criteria. For those EC lines that did not intersect a NEB line, 75 and 100 metre search criterion were also used to manually tag lines after a visual review.

Although the NEB seismic line dataset contains features across the study area, only about 20% of the EC lines were able to be matched to a NEB seismic line. In addition, the NEB seismic line dataset contains both ground and air lines with no differentiation by line source, therefore the resultant temporal information may not yield high-quality results in terms of ground restoration status.

To determine if land cover influences the restoration rate of seismic lines seismic are restored at different rates seismic lines were intersected with the EOSD Integrated Land Cover dataset and NWT FRI land cover dataset in

ArcGIS. Given that the EC seismic lines are considered active disturbances on the land (as of 2010), seismic lines that were not present in the dataset but were present in the NEB seismic line dataset were assumed to be restored. The results of the intersection were then examined for both datasets to see if any correlations were present linking restoration rates to land cover class (e.g., coniferous, broadleaf, mixedwood) and forest resource (e.g., land base, land cover type, land position, vegetation type, vegetation density, and species type).

3.0 RESULTS

3.1 Burn-P3

Full details related to the Burn-P3 results have been provided in Appendix B. The following sections summarize the key findings.

3.1.1 Baseline (2015) Burn Probability

The Baseline (2015) burn probability ranges from a minimum of 0% (non-fuel) to a maximum of 3.76% as summarized in Table 19. The mean probability for the entire study area is 0.59%. Although the maximum burn probability recorded in the study area was 3.76%, the 99th percentile value of the burn probability was 2.78%. The results indicate that only 1% of the grid cells in the study area had a burn probability greater than 2.78%.

Table 19. Summary of Baseline (2015) Burn Probability Statistics

		Burn Probability (%)			
Scenario	**Time Period**	**Minimum**	**Mean**	**99th Percentile**	**Maximum**
Baseline (2015)	2015	0.00	0.59	2.78	3.76

The Baseline (2015) burn probability map (Figure 36) indicates the presence of distinct 'hot spots' of higher burn probability (e.g., to the south of Fort Resolution, to the northeast of Fort Providence, and to the east of Wrigley). A visual analysis of the burn probability map indicates that many of these hot spots are well correlated with the areas classified as grass (O-1) fuel type (Figure 24). In Canada, there are no fuel types specifically developed for shrub cover types (unlike the U.S. fuel type system). Therefore, we are restricted to trying to classify these shrub cover types into one of our 16 defined FBP fuel types. Out of these 16 fuel types, grass is the closest one we have to represent a shrub cover layer.

3.1.2 Climate Change Scenarios

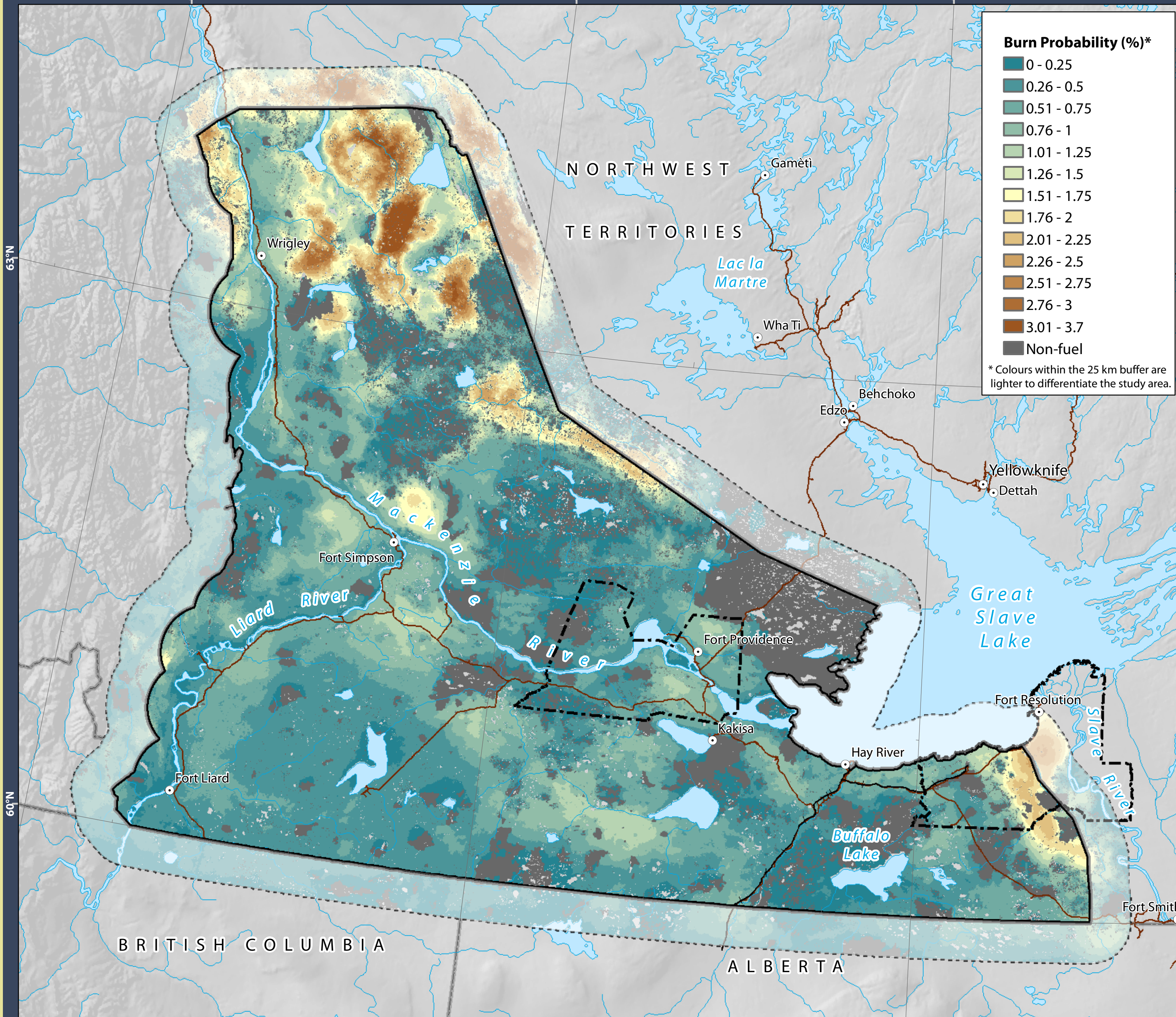
The mean burn probability over the entire study area landscape for all climate change scenarios ranges between 0.76% (CGCM3.1 2080) and 1.05% (HadCM3 2080) (Table 20). The 99th percentile burn probability ranged from 2.42% to 3.21%. When compared against the modelled baseline, the results derived from the CGCM3.1 model indicate relatively stable burn probability levels over time, with both mean and maximum burn probability being similar throughout the time periods. The results derived from the HadCM3 model indicate an increase in both mean and maximum burn probability into the future (Table 20). Figures 37 through 41 illustrate the results of the models derived for each of the climate change scenarios.

Table 20. Summary of Climate Change Scenario Burn Probability Statistics

		Burn Probability (%)			
Scenario	**Time Period**	**Minimum**	**Mean**	**99th Percentile**	**Maximum**
Baseline (Model)	1981 - 2010	0.00	0.85	3.00	3.69
CGCM3.1	2050	0.00	0.81	2.56	3.68
CGCM3.1	2080	0.00	0.76	2.42	3.31
HadCM3	2050	0.00	1.03	3.21	4.39
HadCM3	2080	0.00	1.05	3.14	4.07

Figure 36

Actual Baseline (2015) Scenario Burn Probability



Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

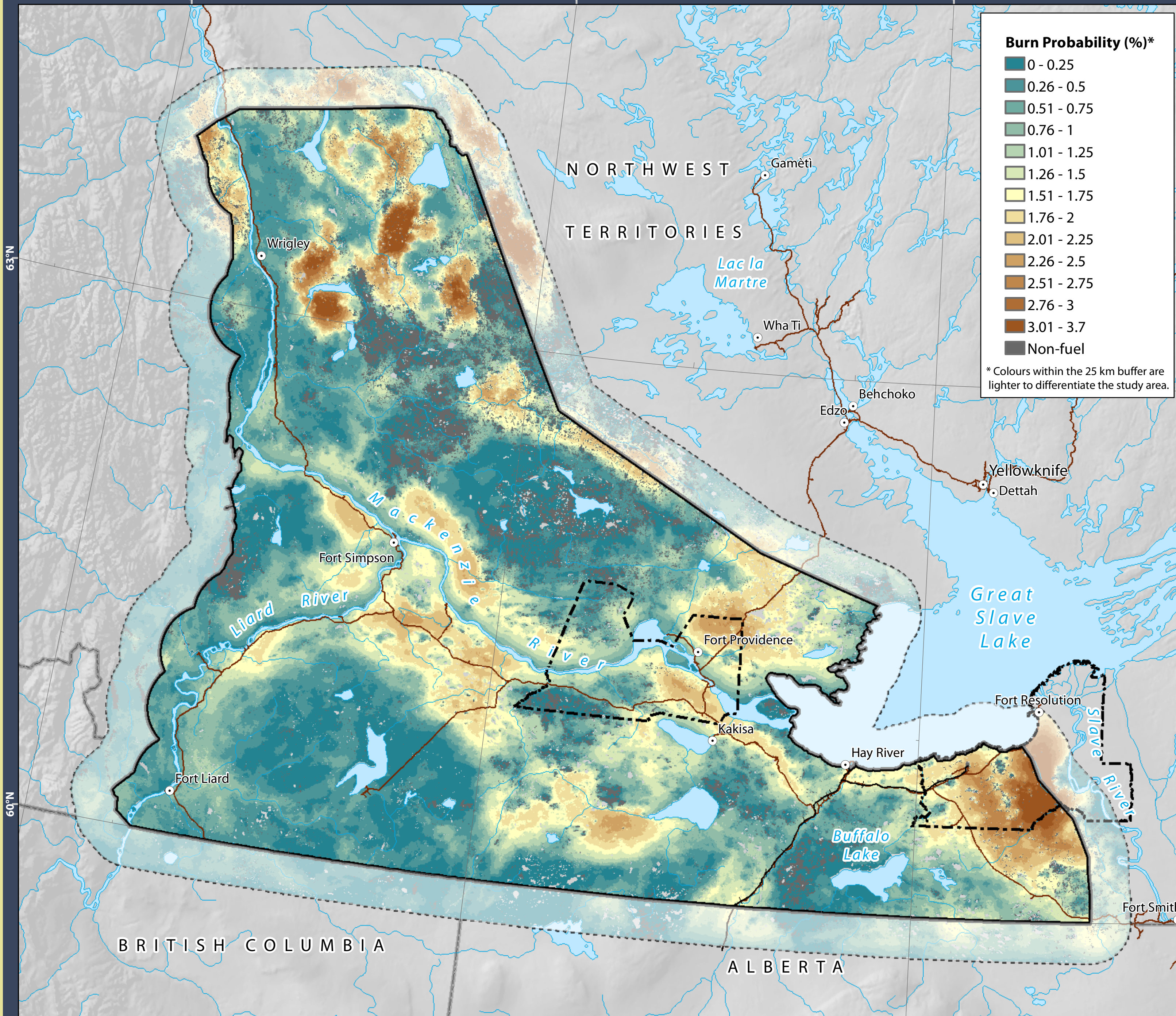
Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

Figure 37

Model Baseline (2015) Scenario Burn Probability



Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

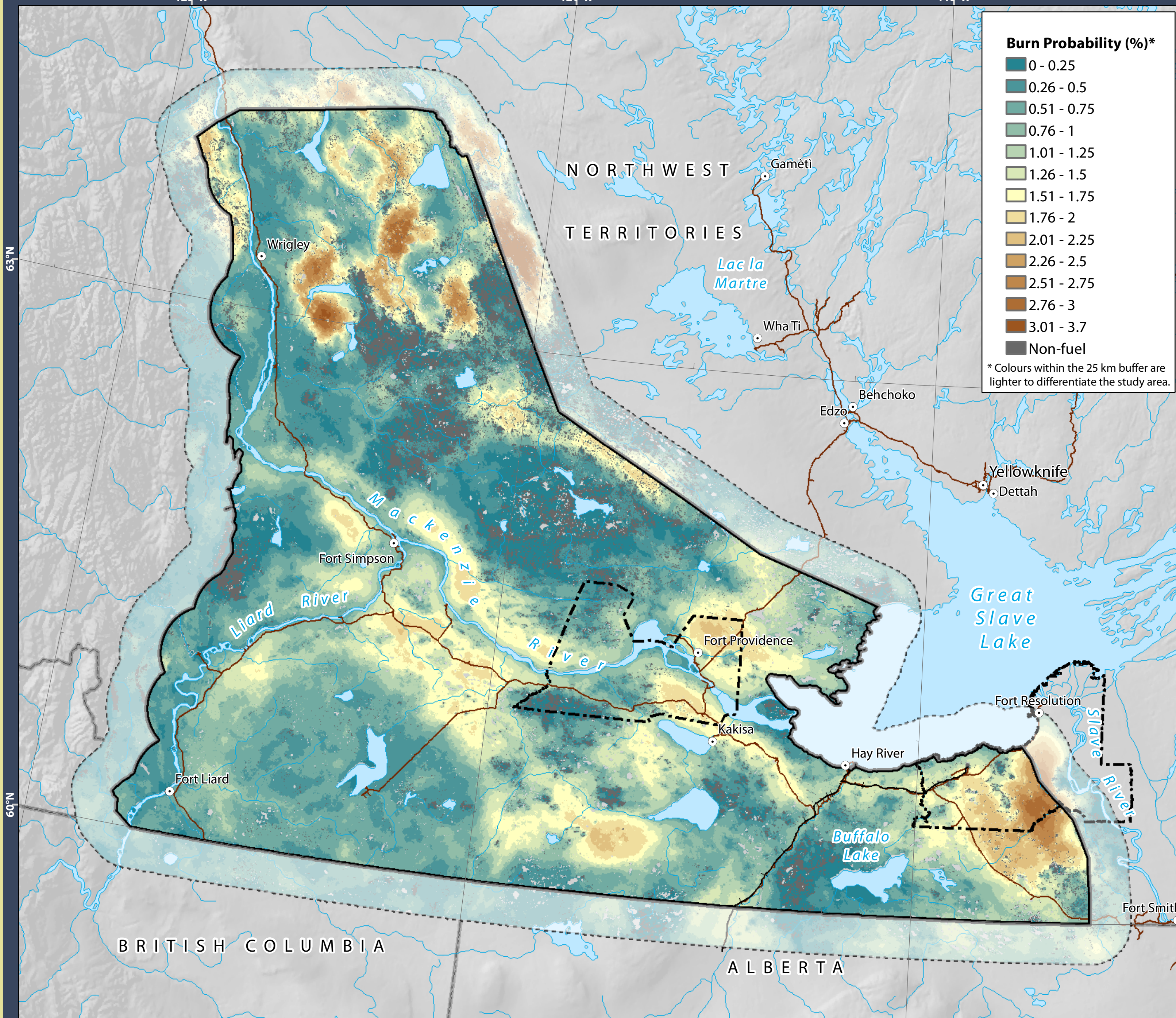
By: CASLYS CONSULTING

March 2016

Figure 38

CGCM3.1 2050 Climate Change Scenario Burn Probability

Community
Railway
Road
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area



0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories
By: CASLYS CONSULTING

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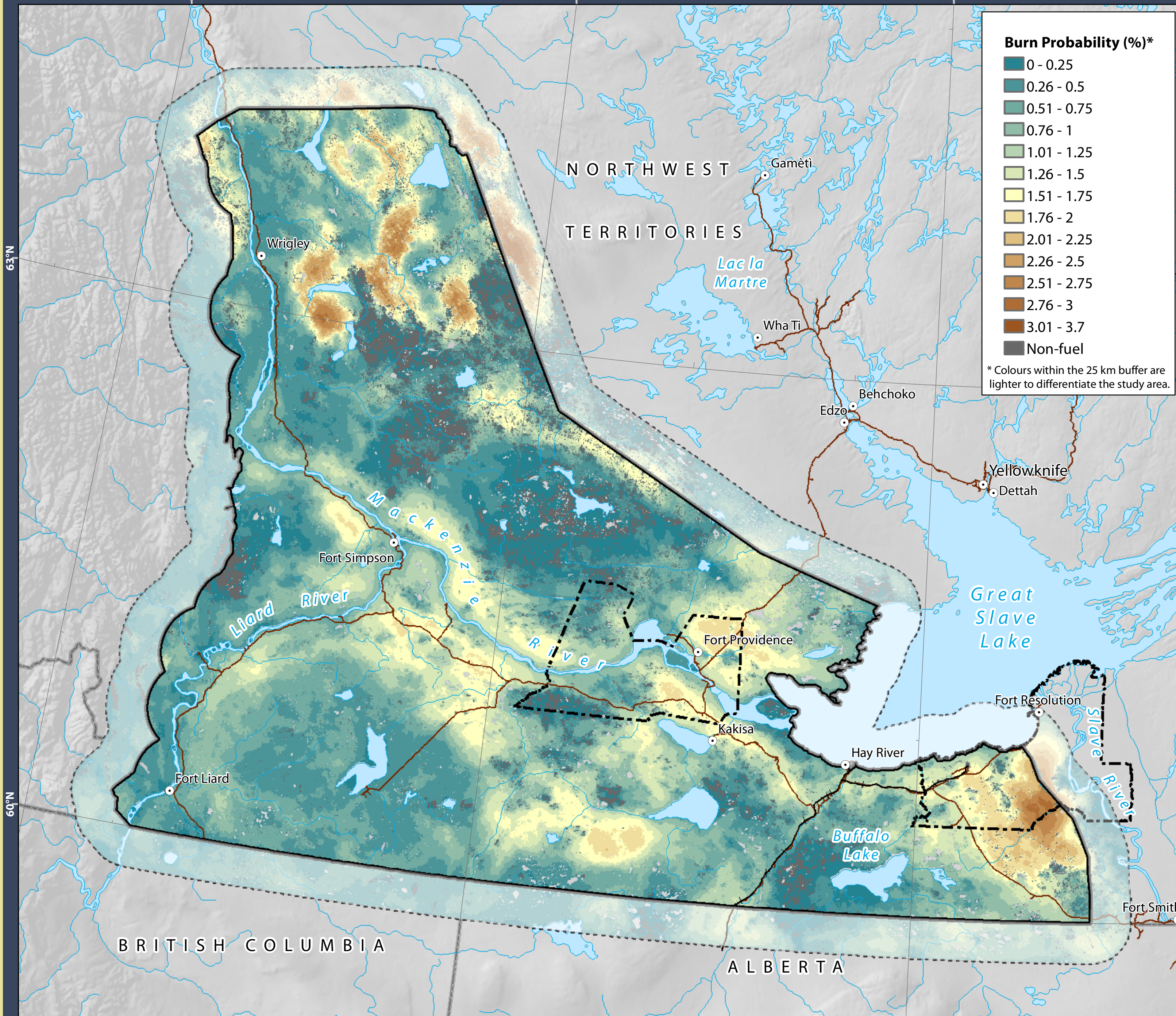
Figure 39

CGCM3.1 2080 Climate Change Scenario Burn Probability



- Community
- Railway
- Road
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

0 50 100

Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

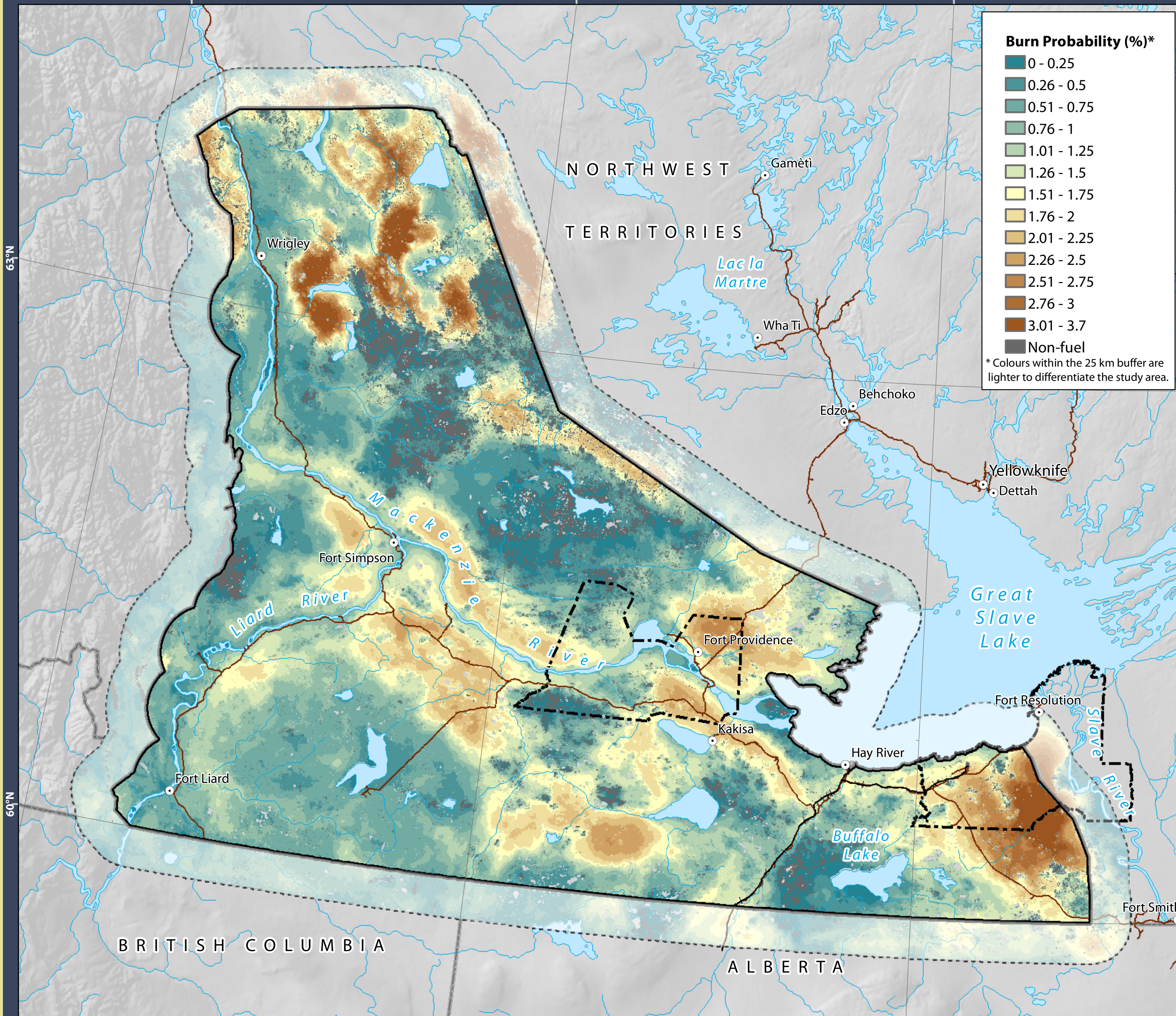


Figure 40

HadCM3 2050 Climate Change Scenario Burn Probability

- Community
- Railway
- Road
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

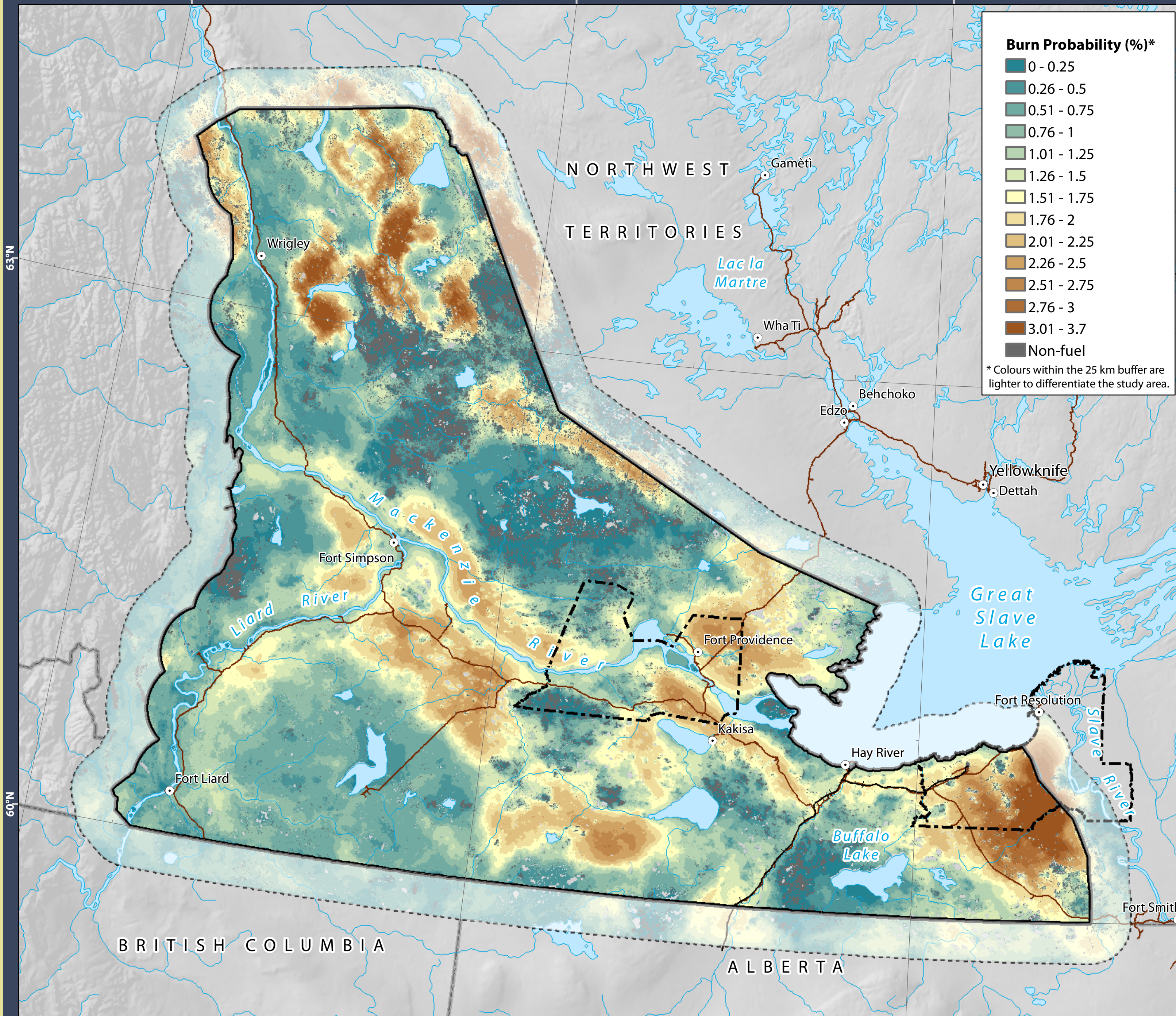
Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

Figure 41

HadCM3 2080 Climate Change Scenario Burn Probability



- Community
- Railway
- Road
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

0 50 100
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

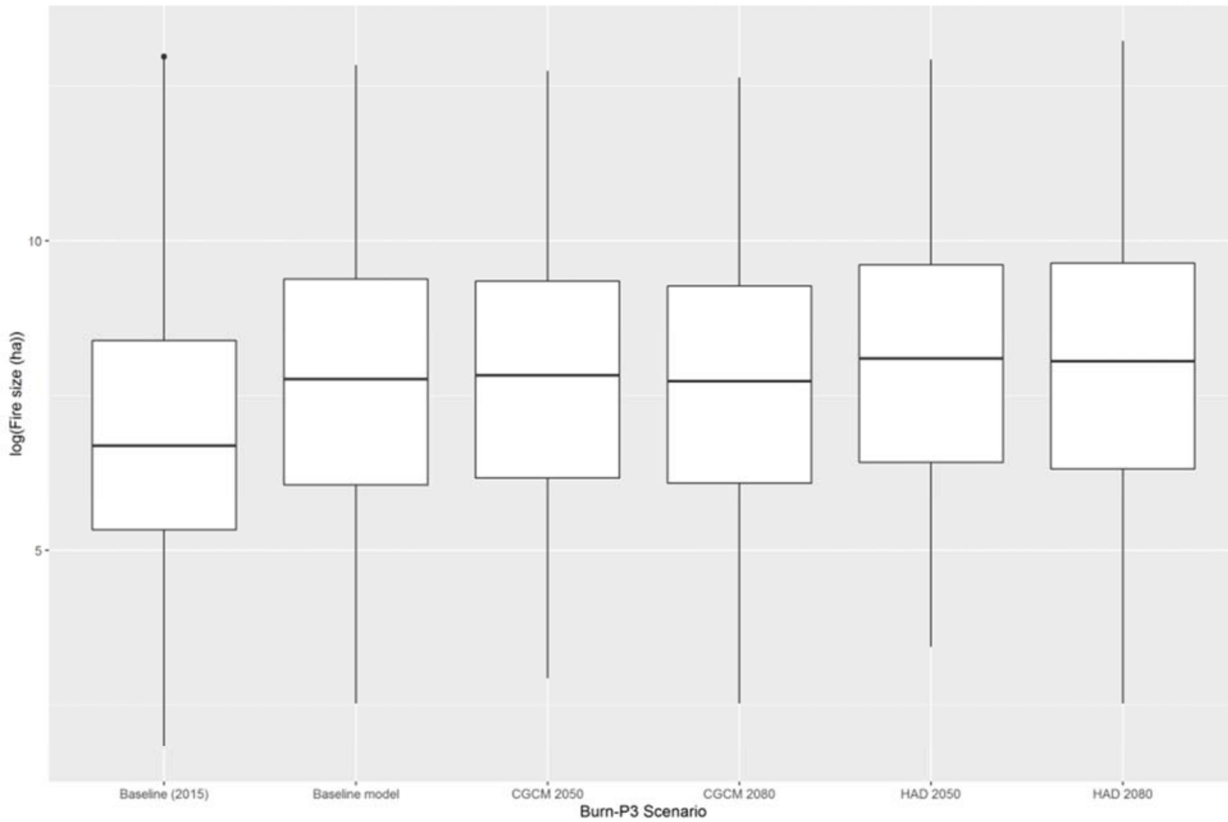
By: CASLYS CONSULTING

March 2016

3.1.3 Fire Size All Scenarios

The distribution of fire size derived for each of the Burn-P3 scenarios is illustrated in Figure 42. The results indicate a general trend toward larger fire sizes into the future.

Figure 42. Fire Size (Median) Distribution Log (ha) of Burn-P3 Simulated Fires by Scenario



3.2 Landscape Projection Results

The landscape projection results are presented in two parts. The first part examines the behaviour and effects of each of the main factors that disturb caribou habitat: existing linear and areal features; future timber harvest and related road development; and fire disturbance. The second part examines the cumulative effects of the three main factors acting in combination on caribou range and on timber harvest.

Only the most likely seismic line recovery and timber harvest scenarios are presented below. Multiple fire disturbance scenarios are presented because uncertainty about future fire behaviour and the influence of alternative assumptions are both high.

Figure 43 shows the current pattern of habitat alteration on the landscape as of 2015, including fires up to 2015. The level and distribution of habitat alteration in Figure 43 corresponds to Year 0 in the figures in the following sections.

3.2.1 Individual Effects of Main Factors

Results in each of the following sections focus on a single disturbance type. The percent undisturbed habitat reported for each section indicates how much habitat would be undisturbed due to that disturbance alone if no other disturbances were present on the landscape. For example, in Section 3.2.1.1, disturbance from existing fires, cutblocks and roads was excluded to assess the impact of only existing linear and areal features. This approach teases apart variables and allows consideration of the relative magnitude of each as well as providing a baseline assessment for the cumulative effects described in the second part.

3.2.1.1 Existing and Linear and Areal Features

In 2015, prior to the start of simulation, approximately 29,500 kilometres of linear anthropogenic features occur within the study area (Table 21). About 4,500 kilometres are considered permanent and do not recover over the course of the simulation. Most of the remaining transient disturbances (~25,000 kilometres) are seismic lines that recover over time (Figure 44). The length of unrecovered seismic lines is based on the recovery rates defined in the seismic lines recovery model (see Section 2.3.7). In each simulation year some raster cells with seismic lines recover based on the recovery rates illustrated in Figure 44.

Table 21. Length of Linear Features in Study Area in 2015 Prior to Simulation, and Type of Change Occurring During Simulation

Feature Lifespan	Linear feature	Length (km)	Projected Trend
Permanent	Airstrip	8	Stable
	Pipeline	51	Stable
	Powerline	273	Stable
	Railway	135	Stable
	Unknown Linear	15	Stable
	Road	3,957	Increasing
	Subtotal	**4,439**	
Transient	Seismic line	25,036	Decreasing
	Total	**29,475**	

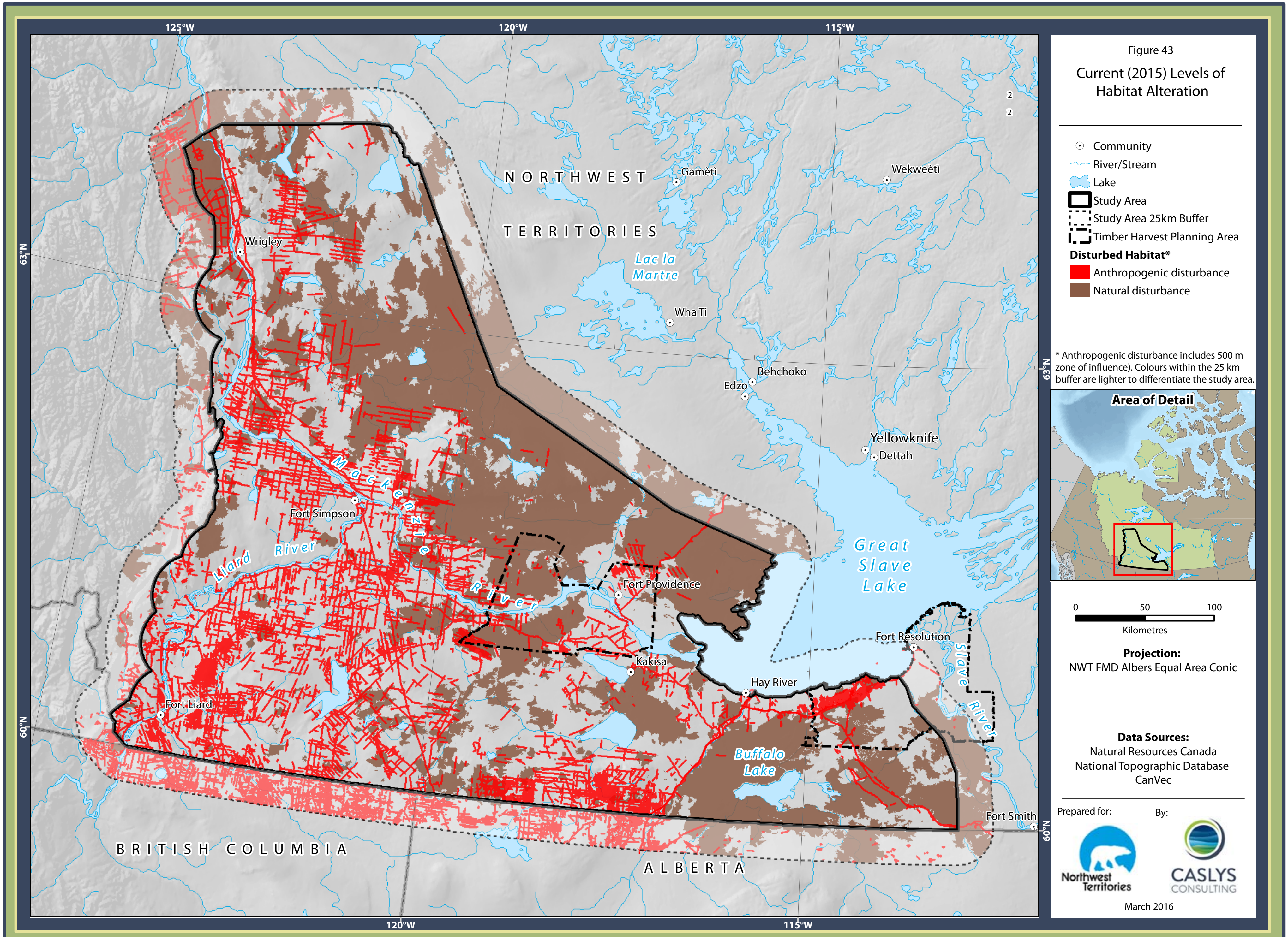
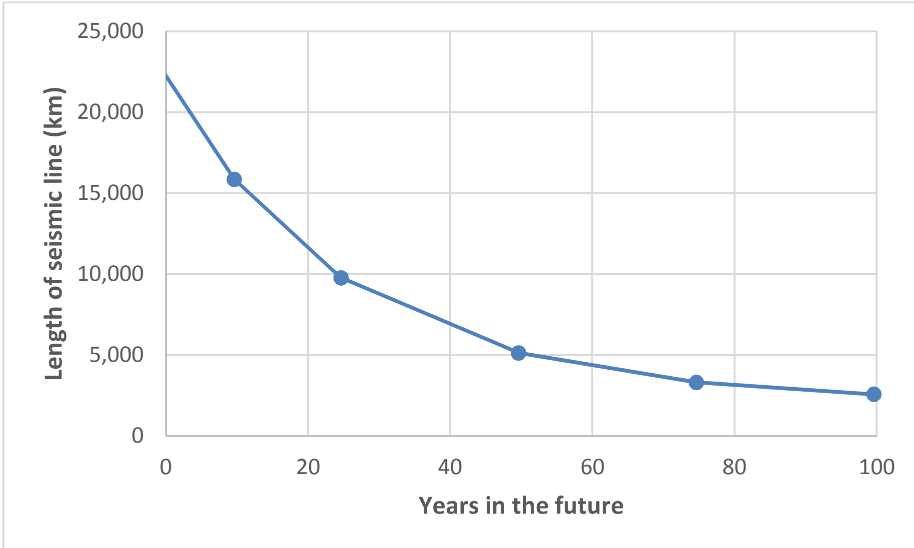

125°W
120°W
115°W
63°N
60°N
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
Gamètì
Wekweètì
Wrigley
Lac la Martre
Wha Ti
Behchoko
Edzo
Yellowknife
Dettah
Mackenzie River
Fort Simpson
Liard River
Great Slave Lake
Fort Providence
Fort Resolution
Slave River
Kakisa
Hay River
Fort Liard
Buffalo Lake
Fort Smith
Figure 43
Current (2015) Levels of Habitat Alteration
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Disturbed Habitat*
Anthropogenic disturbance
Natural disturbance
* Anthropogenic disturbance includes 500 m zone of influence). Colours within the 25 km buffer are lighter to differentiate the study area.
Area of Detail
0
50
100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016

Figure 44. Length of Seismic Lines with Unrecovered Vegetation versus Time (Year 0 = 2015)



Approximately 20,500 ha of areal anthropogenic features cover the landscape in 2015 (Table 22). Of these, approximately 13,500 ha are considered permanent (i.e., they do not change over the 100 year simulation). It is anticipated that the remaining 7,000 ha are cutblocks which will regenerate over time.

Table 22. Area of Existing Areal Anthropogenic Features in the Study Area in 2015 Prior to Simulation, and Type of Change Occurring During Simulation

Feature Lifespan	Areal Feature	Area (ha)	Projected Trend
Permanent	Mine	5,206	Stable
	Oil and Gas	200	Stable
	Settlement	4,169	Stable
	Unknown Areal	2,425	Stable
	Well Site[6]	1,488	Stable
	Subtotal	**13,488**	
Transient	Cutblock	7,038	Increasing
	Total	**20,525**	

Existing linear and areal anthropogenic features, with buffers (500 metres representing the zone of influence around these features), result in approximately 2.25 million ha of disturbed range in the study area. At the start of the simulation, approximately 15% of the study area is disturbed by anthropogenic linear and areal features (Figure 45). With no further development, and the recovery of seismic lines and existing cutblocks, the level of disturbance caused by these features will potentially decrease to about 5% over the next century (Figure 46). Relatively early in the simulation, portions of seismic lines recover and small isolated patches of habitat become connected to the larger habitat matrix by sometimes narrow corridors (Figure 46). Note that results do not vary much by replicates; hence one replicate is presented as a representative example (Figure 47).

[6] For the purposes of this analysis, well sites were considered permanent features. As more information becomes available related to their recovery rate this assumption could be changed however, based on the current level of disturbance (well sites represent only 0.01% of the study area, the impact to the results is negligible.

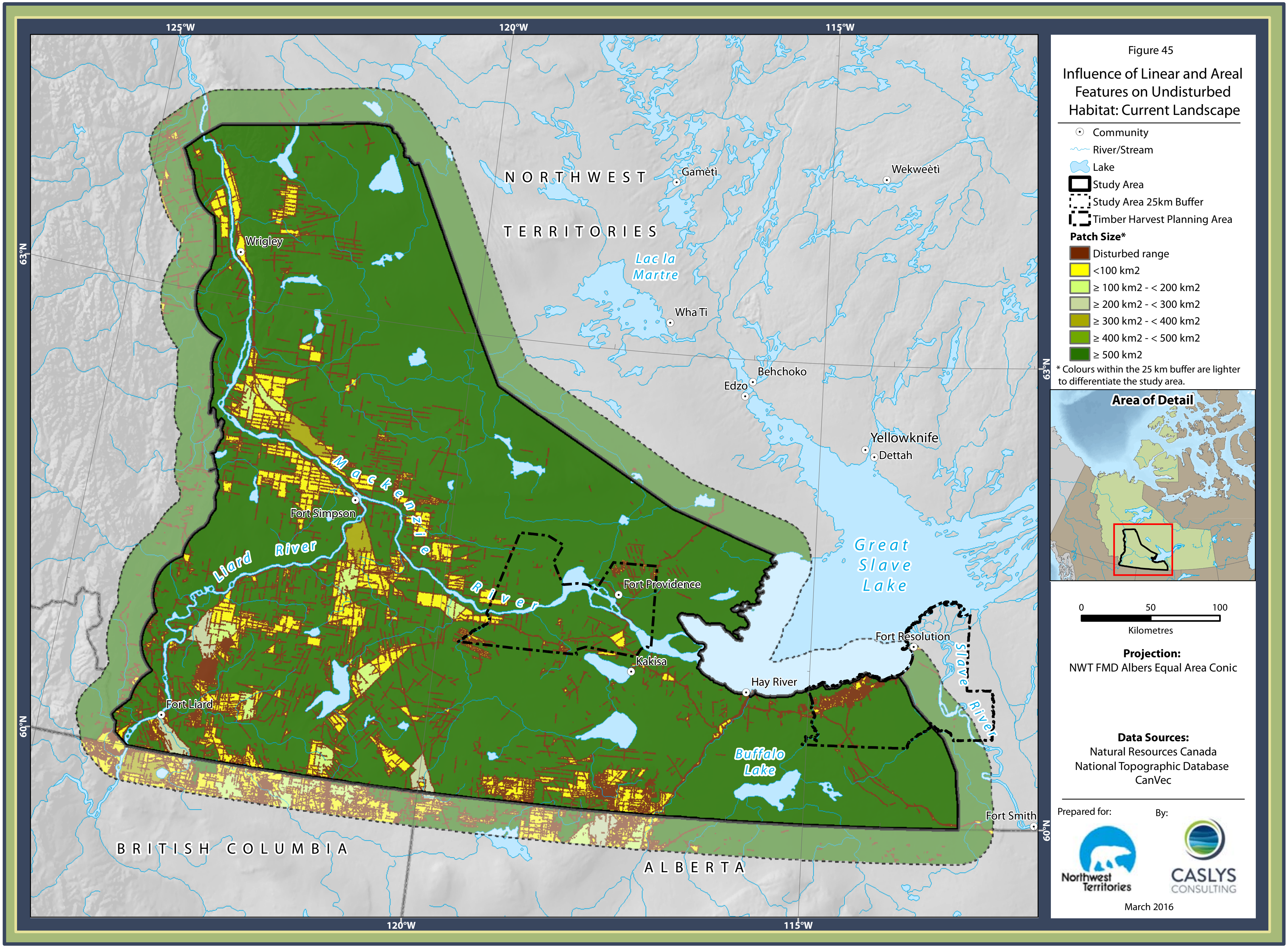
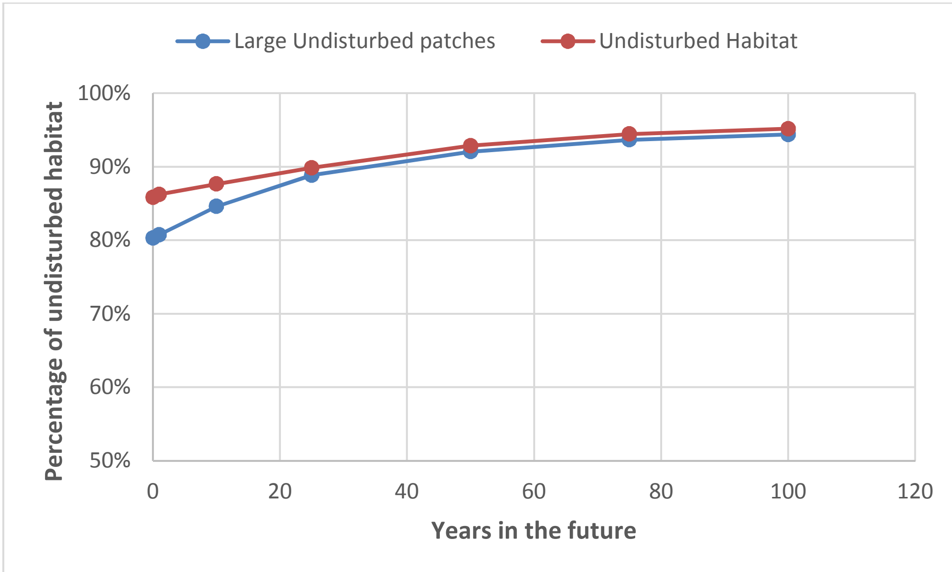


Figure 45
Influence of Linear and Areal Features on Undisturbed Habitat: Current Landscape
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Patch Size*
Disturbed range
<100 km2
≥ 100 km2 - < 200 km2
≥ 200 km2 - < 300 km2
≥ 300 km2 - < 400 km2
≥ 400 km2 - < 500 km2
≥ 500 km2
* Colours within the 25 km buffer are lighter to differentiate the study area.
Area of Detail
0 50 100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
125°W
120°W
115°W
63°N
60°N
Wrigley
Fort Simpson
Fort Liard
Fort Providence
Kakisa
Hay River
Fort Resolution
Fort Smith
Gamètì
Wekweètì
Wha Ti
Behchoko
Edzo
Yellowknife
Dettah
Lac la Martre
Great Slave Lake
Buffalo Lake
Mackenzie River
Liard River
Slave River

Figure 46. Percentage of Study Area with Undisturbed Habitat, due to Linear and Areal Feature versus Time (Year 0 = 2015)*



** Large undisturbed patches represent those >500 km²*

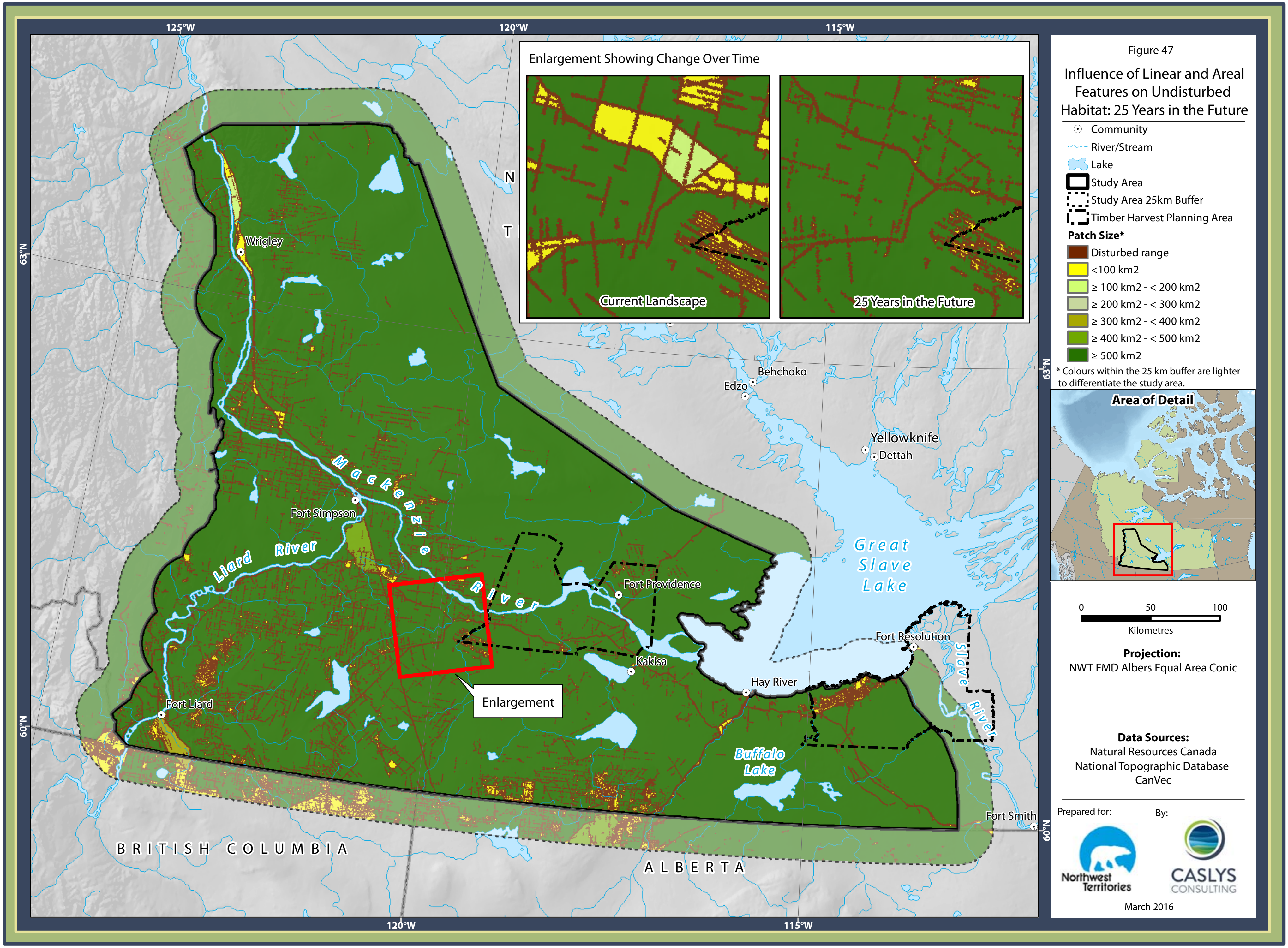


Figure 47
Influence of Linear and Areal Features on Undisturbed Habitat: 25 Years in the Future
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Patch Size*
Disturbed range
<100 km2
≥ 100 km2 - < 200 km2
≥ 200 km2 - < 300 km2
≥ 300 km2 - < 400 km2
≥ 400 km2 - < 500 km2
≥ 500 km2
* Colours within the 25 km buffer are lighter to differentiate the study area.
Area of Detail
0
50
100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
Enlargement Showing Change Over Time
Current Landscape
25 Years in the Future
Enlargement
125°W
120°W
115°W
63°N
60°N
N
T
Wrigley
Fort Simpson
Mackenzie
River
Liard River
Fort Liard
Fort Providence
Kakisa
Hay River
Fort Resolution
Fort Smith
Behchoko
Edzo
Yellowknife
Dettah
Great Slave Lake
Buffalo Lake
Slave River
BRITISH COLUMBIA
ALBERTA

3.2.1.2 New Cutblocks and Access Roads

Commercial forestry is planned in the Fort Providence and Fort Resolution FMA areas. During the simulation, the area of cutblocks increases to reflect timber harvest (figures 48 through 52 show one example). Note that results for timber harvesting do not vary much by replicate; hence we present single replicates as examples, rather than showing medians. Cutblocks recover their caribou habitat value after forty years to reflect recovery of forest vegetation (see Section 2.3.4); some old cutblocks are reharvested near the end of the simulation. Note that these simulations do not include a regeneration delay. The simulation harvests approximately 1,700 ha of the land base annually. The total area of recent cutblocks (i.e., stands < 40 years old) that cause habitat disturbance peaks at 50 years at about 55,000 to 60,000 ha because after that, vegetation recovery counterbalances new harvesting (Figure 53).

Timber harvest in NWT occurs in winter, using winter roads. Winter roads do less damage to soil and organic layers and to natural drainage patterns than do all-season roads and hence are expected to recover over time without deactivation measures. We examined the effect of two road recovery assumptions in Fort Providence FMA: (1) sudden recovery after 40 years of no use; (2) a probability of recovery following the same recovery curve as used for seismic lines. We removed all disturbances not related to timber harvest and focussed on the Fort Providence Forest FMA to better identify small effects that might not be apparent across the larger landscape.

Results for simulations with road recovery did not differ substantially from those without recovery. In Fort Providence, simulations with road recovery had ~2% more undisturbed range in years 75 and 100 than did simulations without road recovery. This translates to a less than 0.2% increase in undisturbed range across the study area. Differences related to recovery rate assumptions (i.e., 40 year versus same as seismic lines) were trivial.

The limited influence of road recovery on undisturbed range reflects the small proportion of roads that recover during simulation. Up to 10% of logging roads constructed during simulation recovered by year 50. Recovered roads ranged from ~15% to 20% of all constructed roads in the latter 50 years of simulation. The small proportion of recovery appears to result from periodic re-use of road networks following a decade or two of disuse and from relatively long recovery periods.

About 2,300 km of new main and branch roads (within-block access is not simulated) are needed to access cutblocks over the next century (Figure 54). In the simulation roads do not recover to caribou habitat. At the start of the simulation, existing cutblocks and the highway leave 99% of the range undisturbed (Figure 55). Simulated timber harvest and related access reduce undisturbed range to 97% (due to timber harvest alone). Timber harvest-related loss of habitat is considerably more pronounced within the THP areas, dropping caribou range to 60% (Figure 56). Timber harvesting also increases fragmentation creating more small patches of habitat (figures 57 and 58). Note that all of the undisturbed range statistics include the 500 metre buffer surrounding disturbance features.

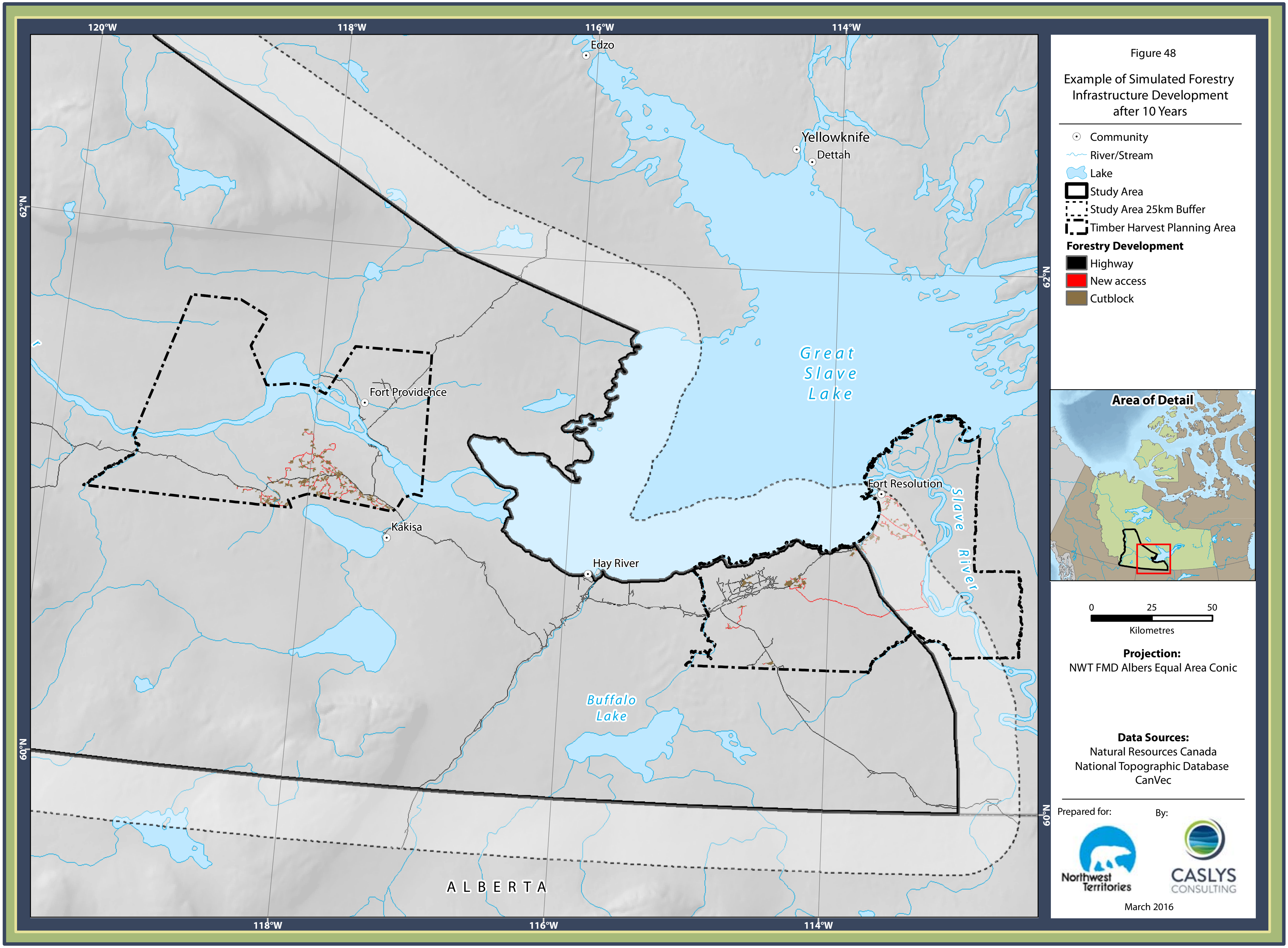


Figure 48
Example of Simulated Forestry Infrastructure Development after 10 Years
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Forestry Development
Highway
New access
Cutblock
Area of Detail
0 25 50
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
Edzo
Yellowknife
Dettah
Great Slave Lake
Fort Providence
Kakisa
Hay River
Fort Resolution
Slave River
Buffalo Lake
ALBERTA
120°W
118°W
116°W
114°W
62°N
60°N

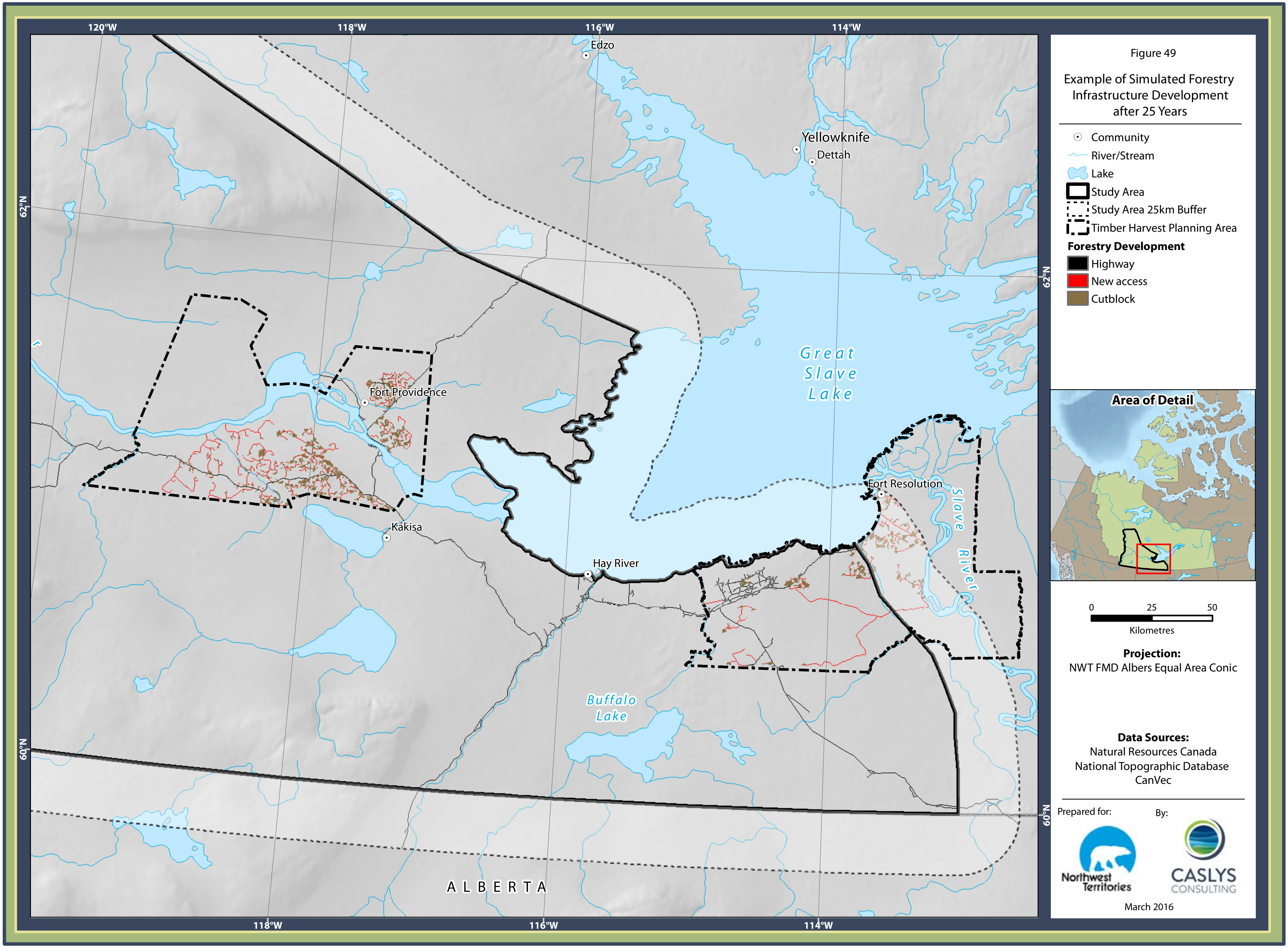


Figure 49
Example of Simulated Forestry Infrastructure Development after 25 Years
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Forestry Development
Highway
New access
Cutblock
Area of Detail
0
25
50
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
120°W
118°W
116°W
114°W
62°N
60°N
Edzo
Yellowknife
Dettah
Great Slave Lake
Fort Providence
Kakisa
Hay River
Fort Resolution
Slave River
Buffalo Lake
ALBERTA

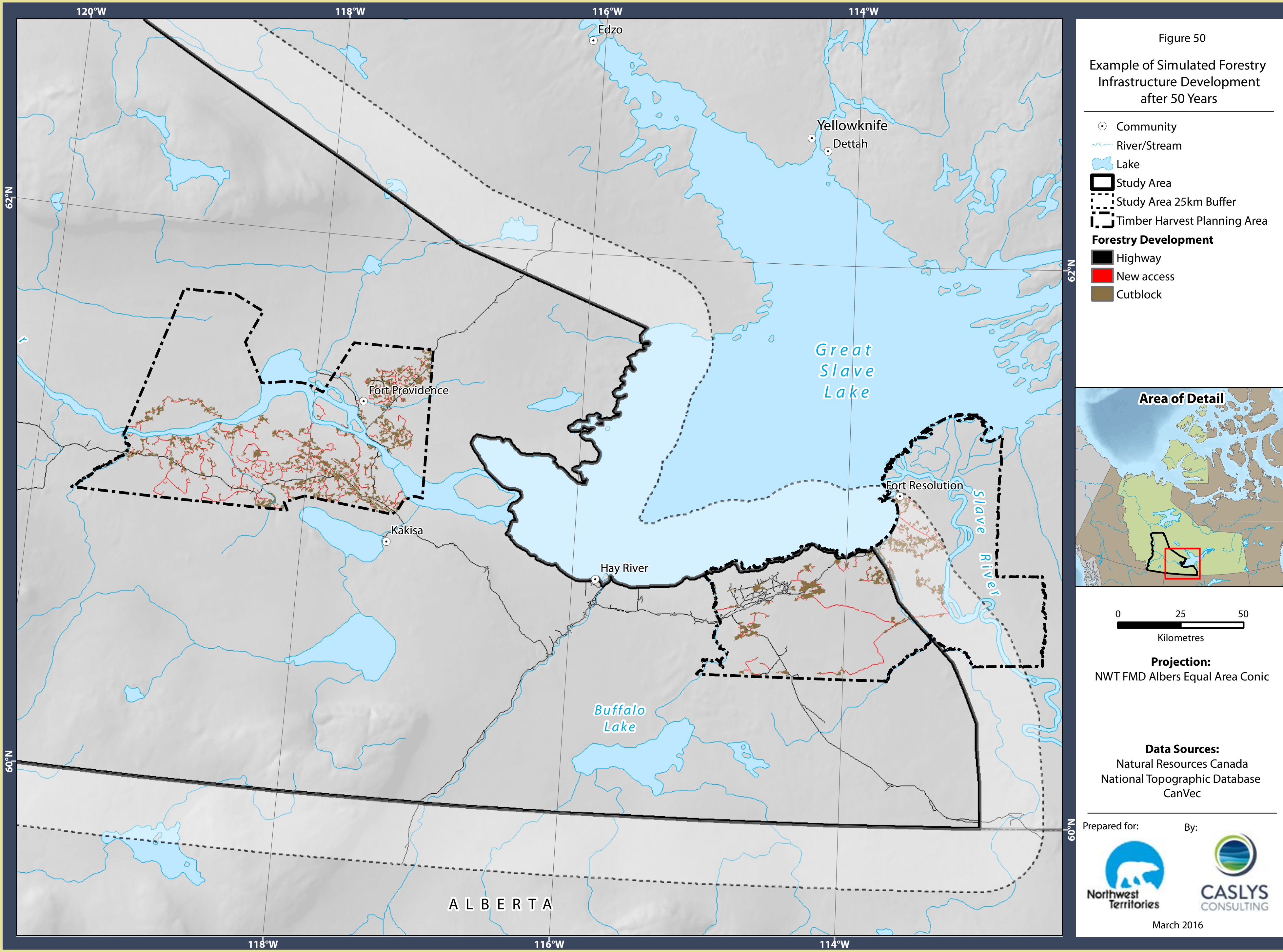


Figure 50

Example of Simulated Forestry Infrastructure Development after 50 Years

- Community
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

Forestry Development

- Highway
- New access
- Cutblock

0 25 50

Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

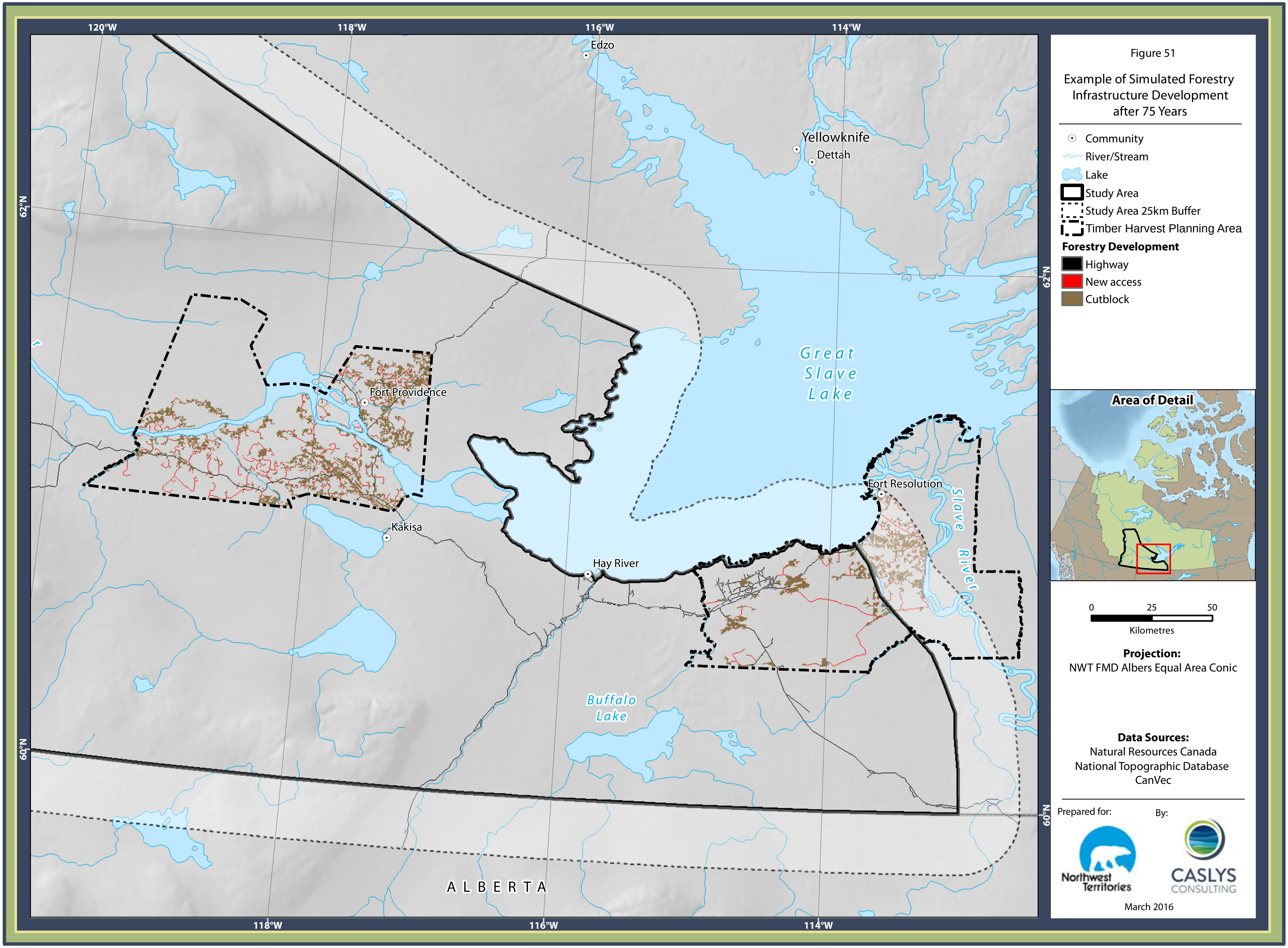


Figure 51
Example of Simulated Forestry Infrastructure Development after 75 Years
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Forestry Development
Highway
New access
Cutblock
Area of Detail
0
25
50
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
120°W
118°W
116°W
114°W
62°N
60°N
Edzo
Yellowknife
Dettah
Great Slave Lake
Fort Providence
Kakisa
Hay River
Fort Resolution
Slave River
Buffalo Lake
ALBERTA

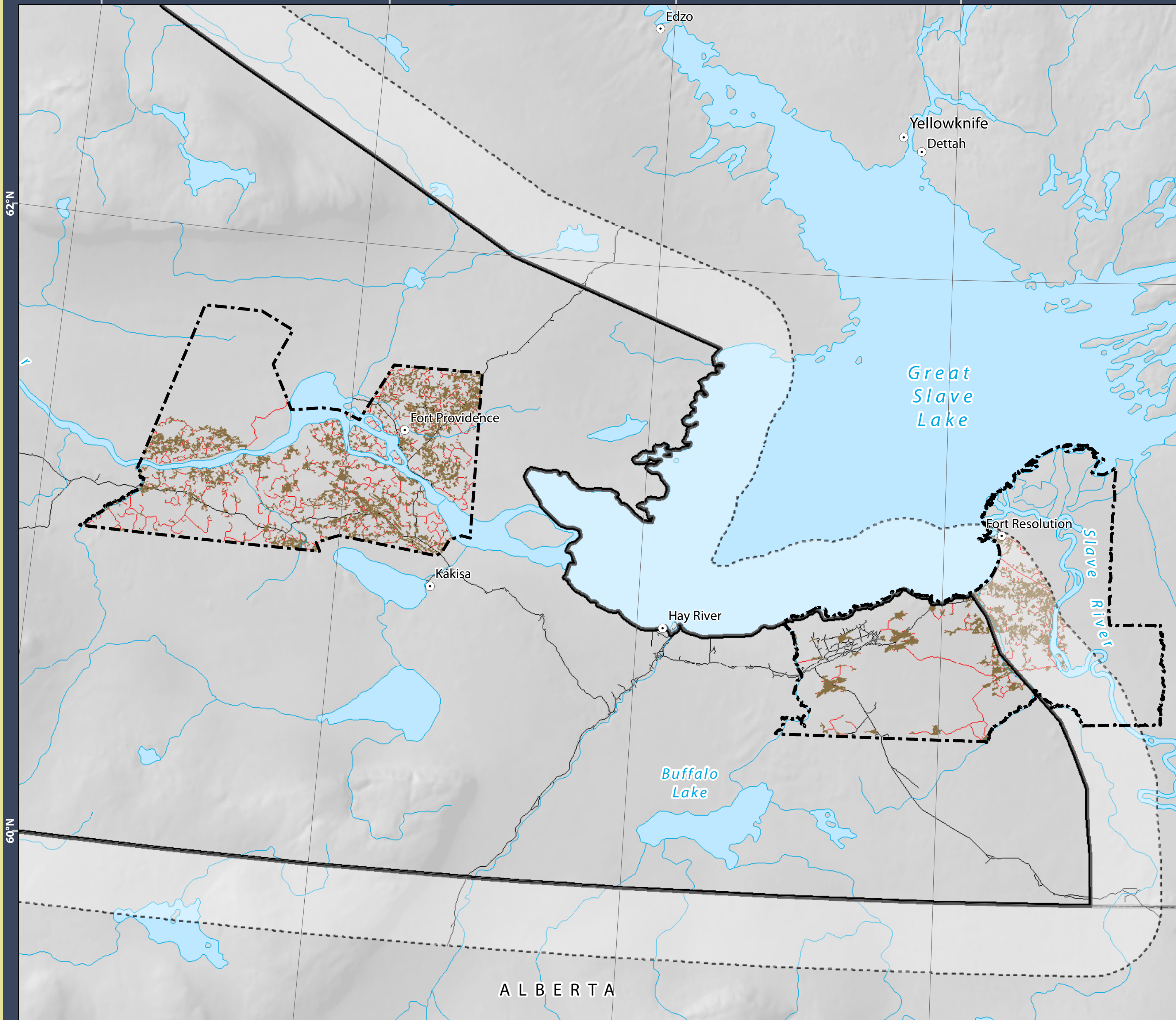


Figure 52

Example of Simulated Forestry Infrastructure Development after 100 Years

- Community
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

Forestry Development

- Highway
- New access
- Cutblock

0 25 50
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories
By: CASLYS CONSULTING

March 2016

Figure 53. Area of Cutblocks Harvested within the Previous 40 Years (Year 0 = 2015)

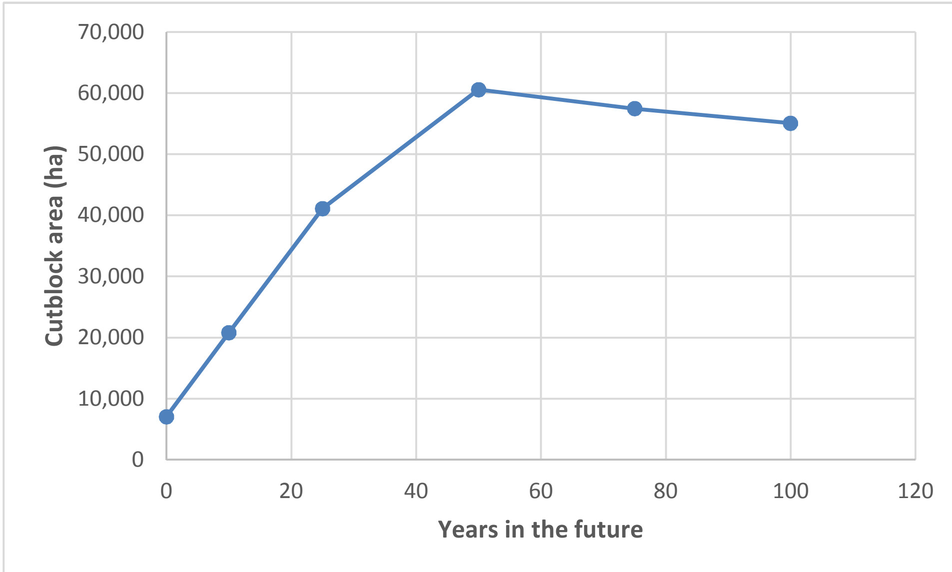


Figure 54. Length of New Timber Harvest-related Access Roads in the Fort Providence and Fort Resolution FMAs (Year 0 = 2015)

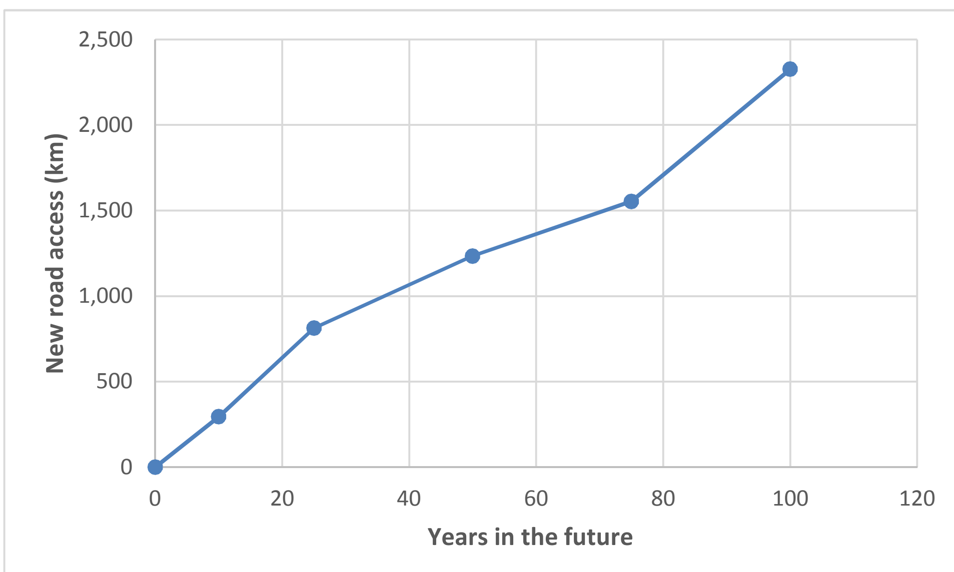
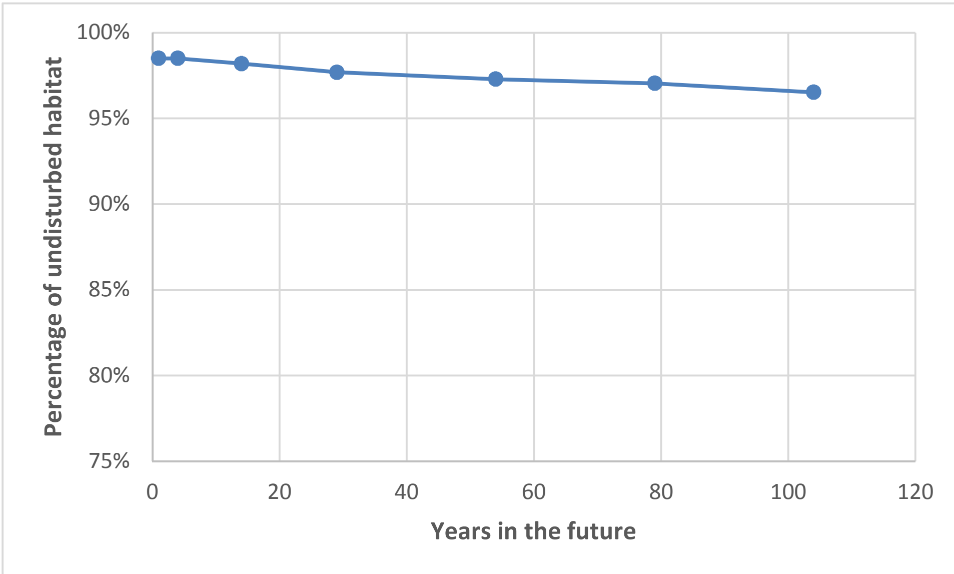
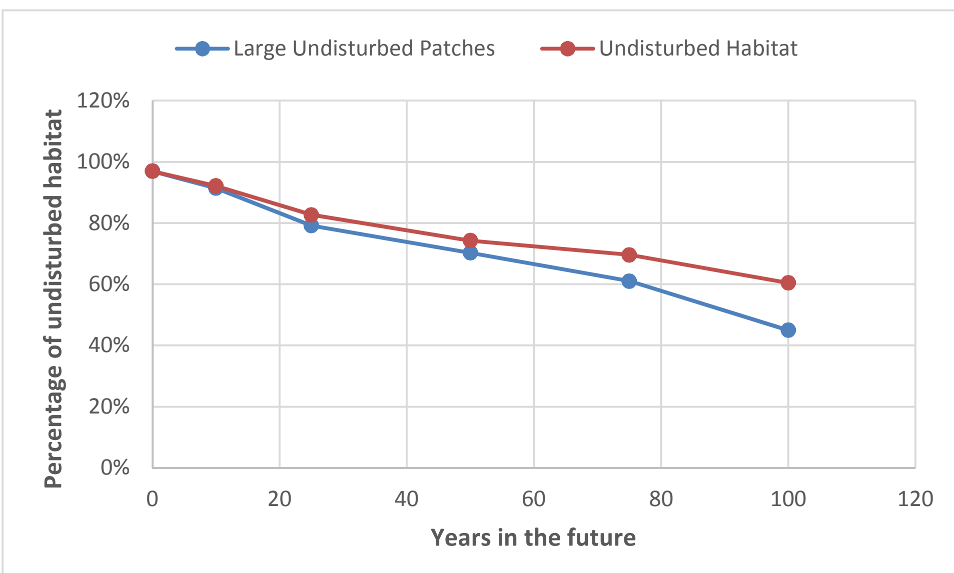


Figure 55. Percentage of Undisturbed Habitat in the Study Area, Related to Cutblocks, Access Roads and the Highway over Time (Year 0 = 2015)*



** The 500 metre buffer surrounding disturbance features has been excluded from all undisturbed habitat calculations.*

Figure 56. Percentage of Fort Providence FMA with Undisturbed Habitat, due to Timber Harvest and Related Access over Time (Year 0 = 2015)*



** Large undisturbed patches represent those >500 km^2. The 500 metre buffer surrounding disturbance features has been excluded from all undisturbed habitat calculations.*

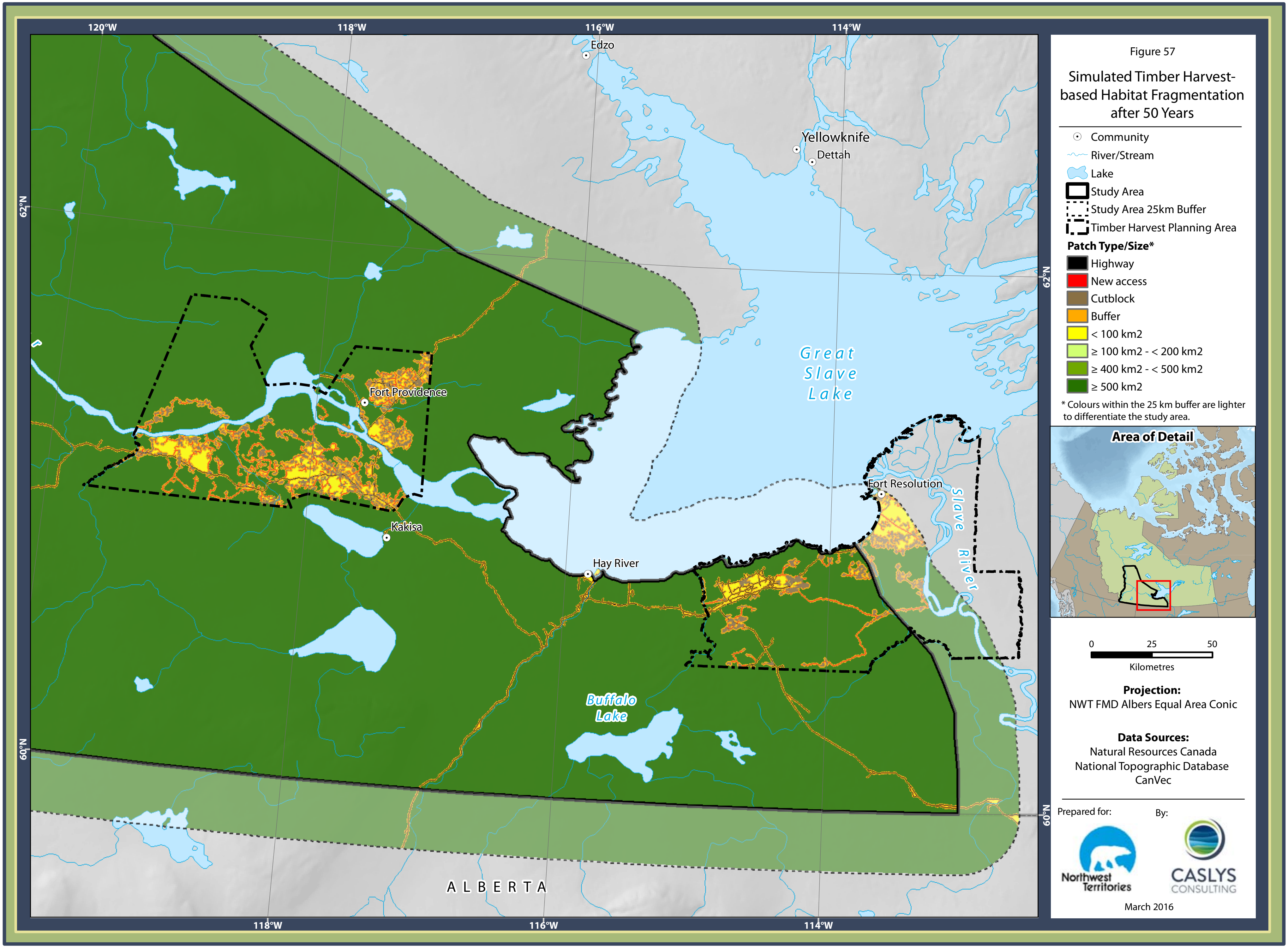


Figure 57
Simulated Timber Harvest-based Habitat Fragmentation after 50 Years
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Patch Type/Size*
Highway
New access
Cutblock
Buffer
< 100 km2
≥ 100 km2 - < 200 km2
≥ 400 km2 - < 500 km2
≥ 500 km2
* Colours within the 25 km buffer are lighter to differentiate the study area.
Area of Detail
0
25
50
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
120°W
118°W
116°W
114°W
62°N
60°N
Edzo
Yellowknife
Dettah
Great Slave Lake
Fort Providence
Kakisa
Hay River
Fort Resolution
Slave River
Buffalo Lake
ALBERTA

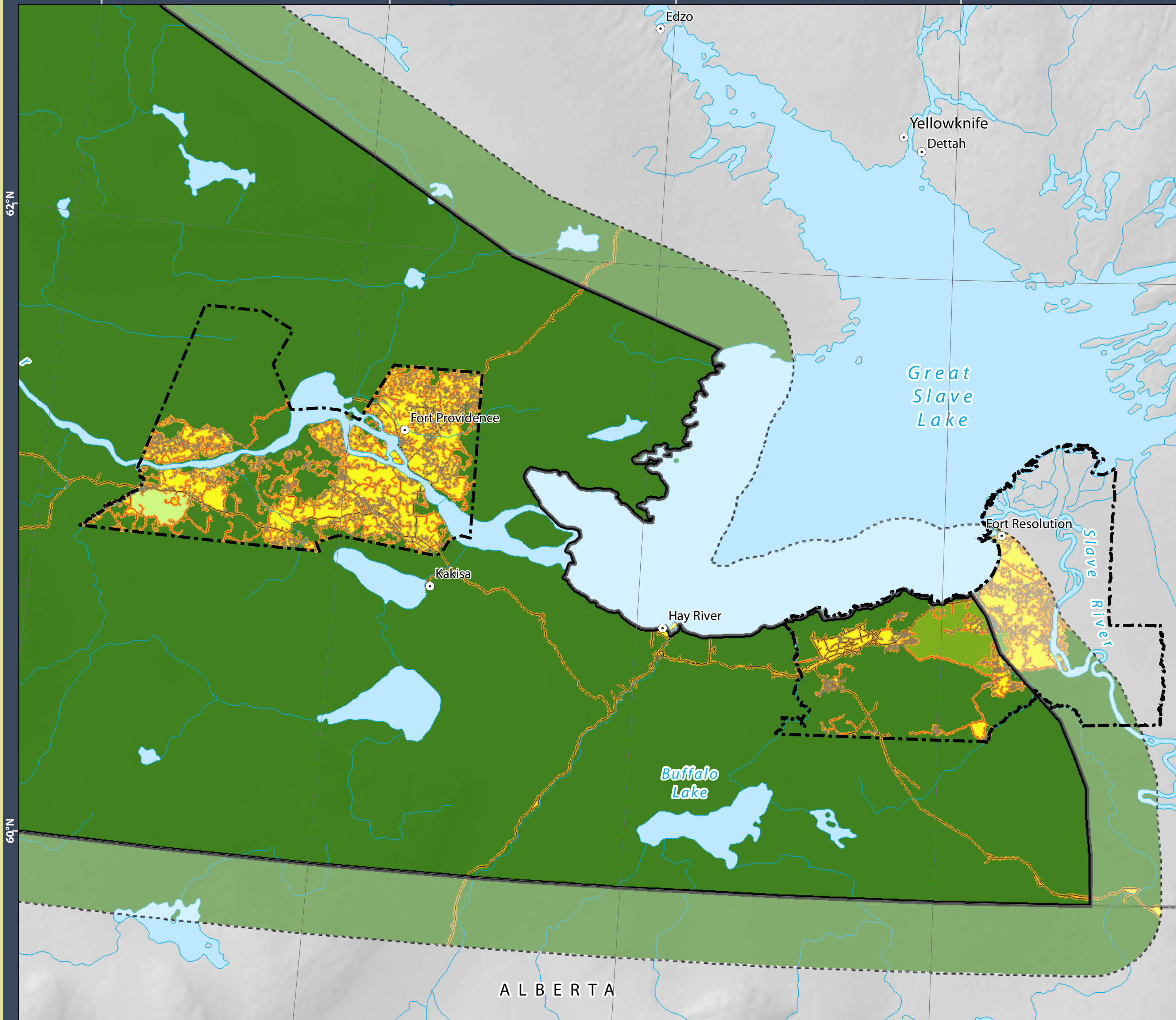


Figure 58

Simulated Timber Harvest-based Habitat Fragmentation after 100 Years

- Community
- River/Stream
- Lake
- Study Area
- Study Area 25km Buffer
- Timber Harvest Planning Area

Patch Type/Size*

- Highway
- New access
- Cutblock
- Buffer
- < 100 km2
- ≥ 100 km2 - < 200 km2
- ≥ 400 km2 - < 500 km2
- ≥ 500 km2

* Colours within the 25 km buffer are lighter to differentiate the study area.

0 25 50
Kilometres

Projection:
NWT FMD Albers Equal Area Conic

Data Sources:
Natural Resources Canada
National Topographic Database
CanVec

Prepared for: Northwest Territories

By: CASLYS CONSULTING

March 2016

3.2.1.3 Fire

Fire disturbance scenarios (Table 23) are defined by combinations of climate projections (on the left) and fuel recovery assumptions (on the right). For example, scenarios were generated using the HadCM3 climate projection values using each of the five fuel recovery assumptions to facilitate a comparison of the results. The fuel recovery scenarios were based on a three simple options: a) immediate recovery; b) in 50 years; and c) 50 years with a 25 year lag period (see Section 2.3.4.1). To examine more complex fuel recovery scenarios, two additional fuel recovery assumptions were considered: d) recolonization with succession; and e) recolonization and succession with a 50 year delay (see Section 2.3.4.2). For both the simple and complex assumptions, the 50 year time period was based on a recovery rate of 2% per year (Figure 29).

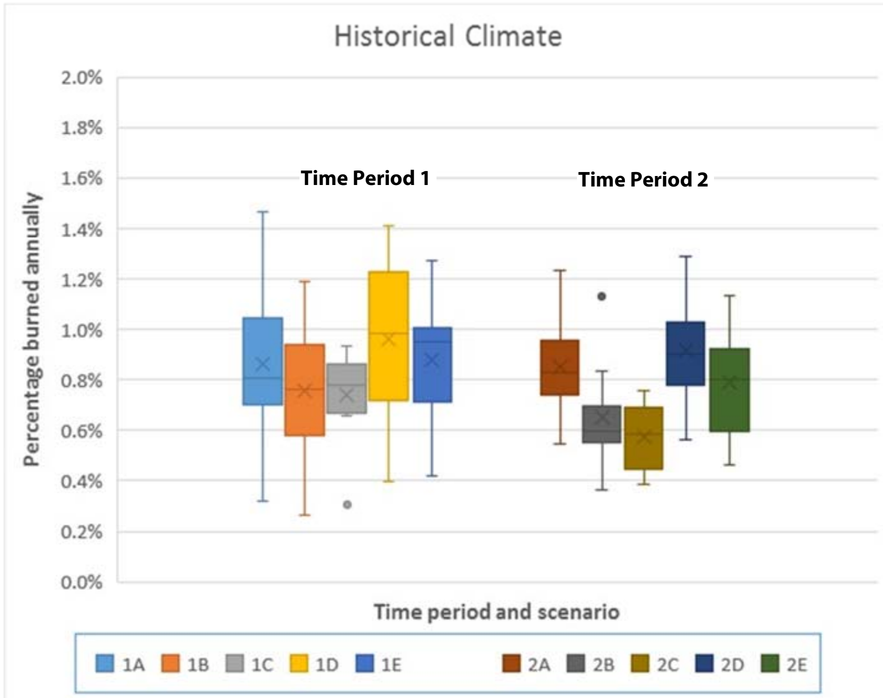
Table 23. Climate and Fuel Recovery Assumptions used to Create Fire Scenarios

Future Climate
Historical
HadCM3
CGCM3.1

Fuel Recovery	
A)	Immediate
B)	50 years
C)	Regeneration lag + 25 years
D)	Recolonization/Succession
E)	Recolonization/Succession + 50 years

Under historical climates, average area burned depends somewhat on fuel recovery rate (Figure 59). Immediate fuel recovery (scenario A) produces a relatively high and stable burned area over time, essentially re-burning the historical landscape and providing a baseline for comparison. Slower fuel recovery (scenarios B and C) tend to reduce the average flammability (spread rate) of fuels across the landscape and reduce area burned; this effect occurs mainly from 50 to 100 years in the simulation. The net effect of recolonization with less-flammable deciduous species combined with succession to more-flammable coniferous species (scenario D) tends to increase area burned relative to the baseline immediate recovery. Combining slow fuel recovery with recolonization/succession produces an intermediate result. Variability in area burned among replicates is high so scenario results are difficult to distinguish statistically. In the second 50-year period, slow recovery scenarios (2B, 2C) overlap least with the baseline immediate recovery scenario (2A).

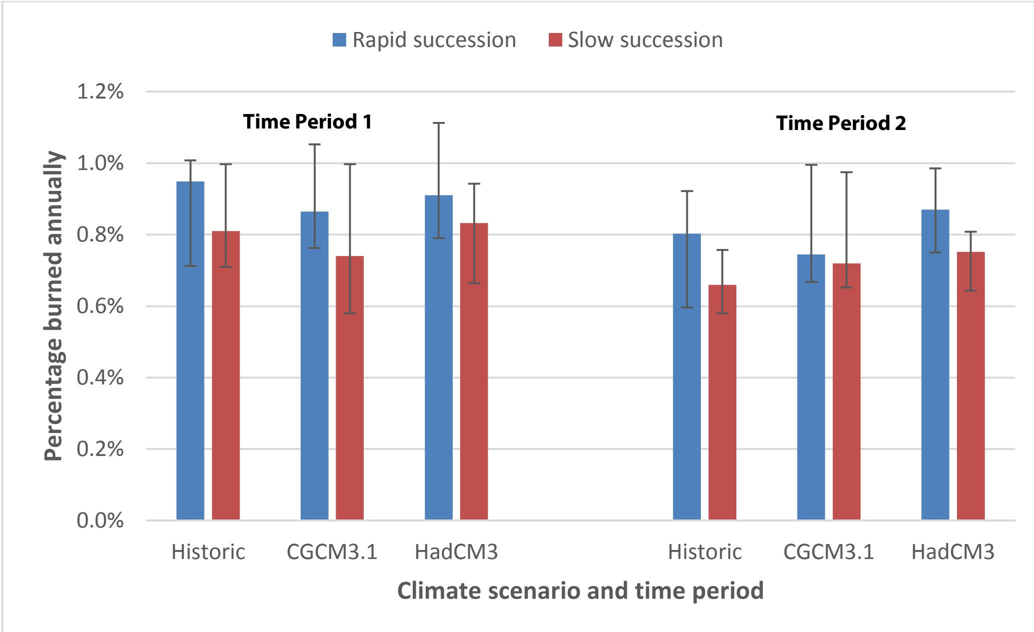
Figure 59. Percentage of Study Area Burned (boxplot quartiles and mean X) for Different Time Periods and Scenarios with Historical and Projected Future (HadCM3) Climates*



** Time periods are 1 (1 to 50 years) and 2 (51 to 100 years). Scenarios correspond to the following: A) Immediate fuel recovery; B) 50-year fuel recovery; C) regeneration delay with 25-year fuel recovery; D) Recolonization and succession; E) Combination of 50-year fuel recovery with recolonization and succession.*

Slowing the rate of succession reduces area burned. In the model, the rate of succession of deciduous species to coniferous species is determined by an aspen 'survival' parameter. Shifting year to year survival rate from 98.5% (rapid succession) to 99% (slow succession) reduces percent area burned annually by ~0.1% (Figure 60).

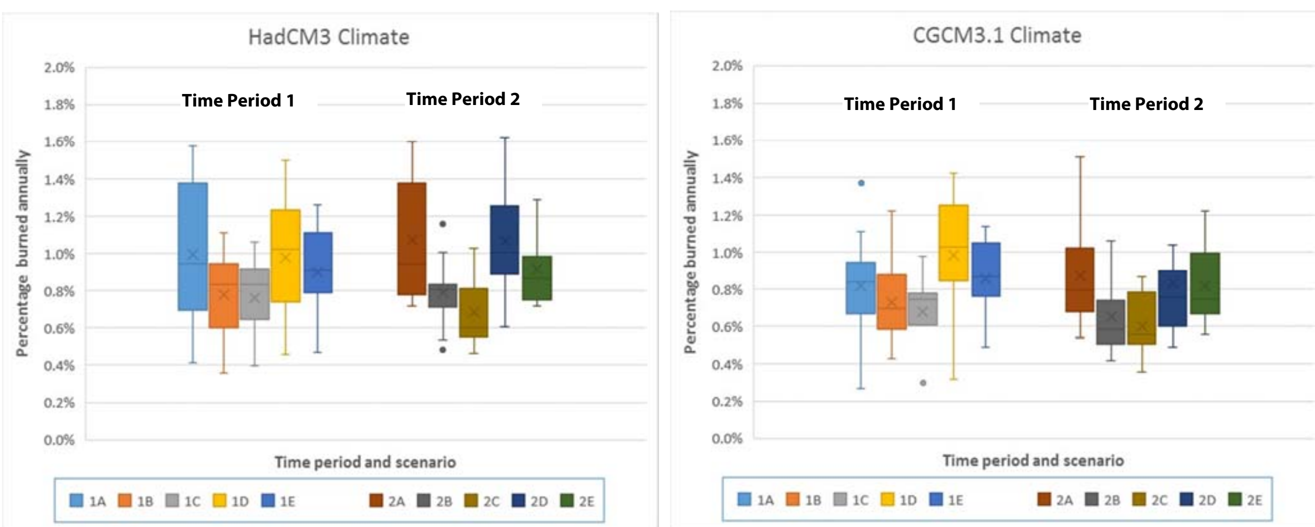
Figure 60. Percentage of Study Area Burned annually in Models with Rapid versus Slow Succession, Across Three Climate Scenarios*



**All models use 50-year fuel recovery. Bars on the left are for years 1 to 50; bars on the right are for years 51 to 100.*

The effects of climate change on area burned depends on the climate model used. Relative to historical climate and CGCM3.1 climate projections, the HadCM3 model's hotter and drier projections lead to a slight increase in average area burned, and a larger increase in the number of fires that burn more than one percent per year (Figure 61). Slower fuel recovery (scenarios B, C and E) buffer the increase. Area burned under the CGCM3.1 model is similar to under historical climate.

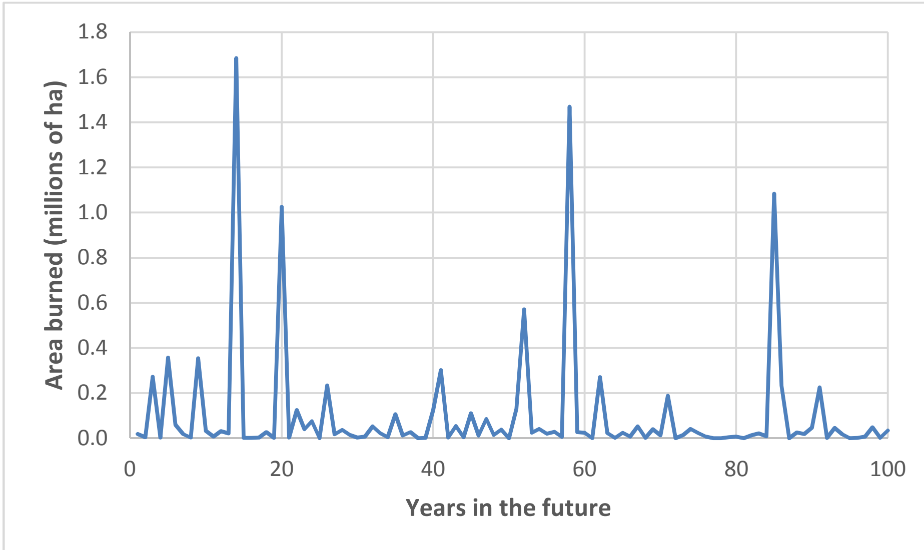
Figure 61. Percentage of Study Area with Burned Habitat (boxplot quartiles and mean X) for Different Time Periods and Scenarios with Projected Future (HadCM3 and CGCM3.1) Climates*



** Time periods are 1 (1 to 50 years) and 2 (51 to 100 years). Scenarios include A) immediate fuel recovery; B) 50-year fuel recovery; C) regeneration delay with 25-year fuel recovery; D) recolonization and succession; E) combination of 50-year fuel recovery with recolonization and succession.*

Area burned varies substantially among years in all simulations. Figure 62 provides an example of one simulation run of the immediate fuel recovery scenario, with an average annual burn of 0.7 % of the study area.

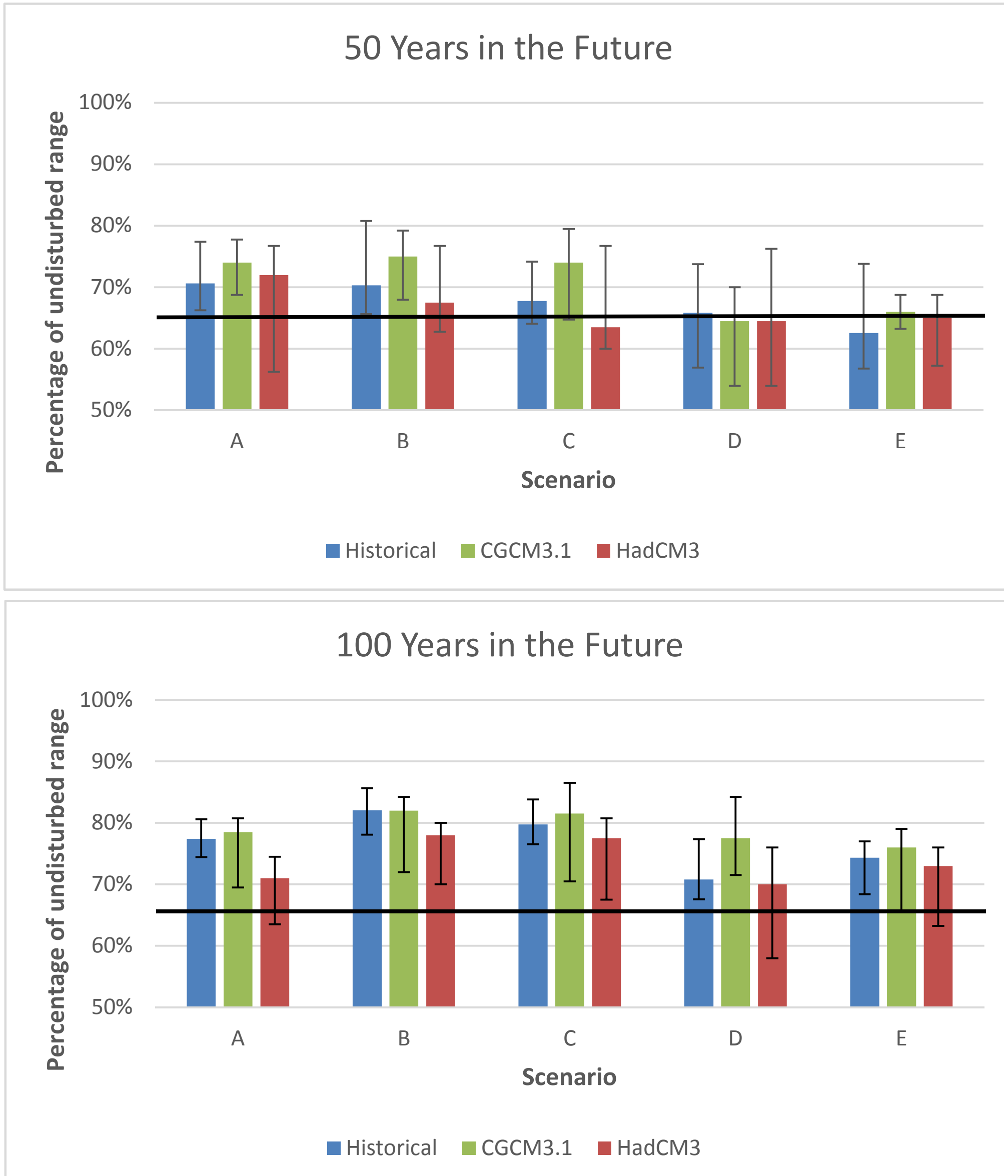
Figure 62. Area Burned (Millions of Hectares) within the Study over the Simulation (Year 0 = 2015)



Historically, fires have disturbed a substantial amount of the caribou range. In 2011, undisturbed range (i.e., > 40 years since fire) related to fires covered 69% of the study area. In 2015, following several large fires, range undisturbed by fire covered 62% of the study area.

Undisturbed range projections vary with year, climate model and scenario (Figure 63). In general, the CGCM3.1 climate projection increases the amount of undisturbed range while the HadCM3 climate projection reduces range, relative to projections based on historical climate data. Scenarios with succession (D, E) tend to reduce caribou range relative to scenarios with slow fuel recovery (B, C). In general, year 100 has more range than year 50.

Figure 63. Percentage of Range Undisturbed by Recent Fire (< 40 years) for Different Sample Years, Scenarios and Climate Projections*



** Scenarios: A) immediate fuel recovery; B) 50-year fuel recovery; C) regeneration delay with 25-year fuel recovery; D) recolonization and succession; E) combination of 50-year fuel recovery with recolonization and succession.*

3.2.2 Effects of Combined Factors

The following sections explore the effects of timber harvest and fire disturbance on undisturbed range abundance within a cumulative-effects simulation model that includes climate change, fire, fuel recovery and succession, timber harvest, existing linear and areal disturbance and habitat recovery (from fire, timber harvest and seismic lines). Twelve scenarios examine the effects of different combinations of timber harvesting, climate change and fuel succession assumptions (Table 24). Each scenario has 10 replicates (total of 120 simulation runs for all scenarios) to characterize variability within the scenario. The twelve scenarios considered in this section include the parameter combinations deemed to be most plausible. They are not testing extreme assumptions.

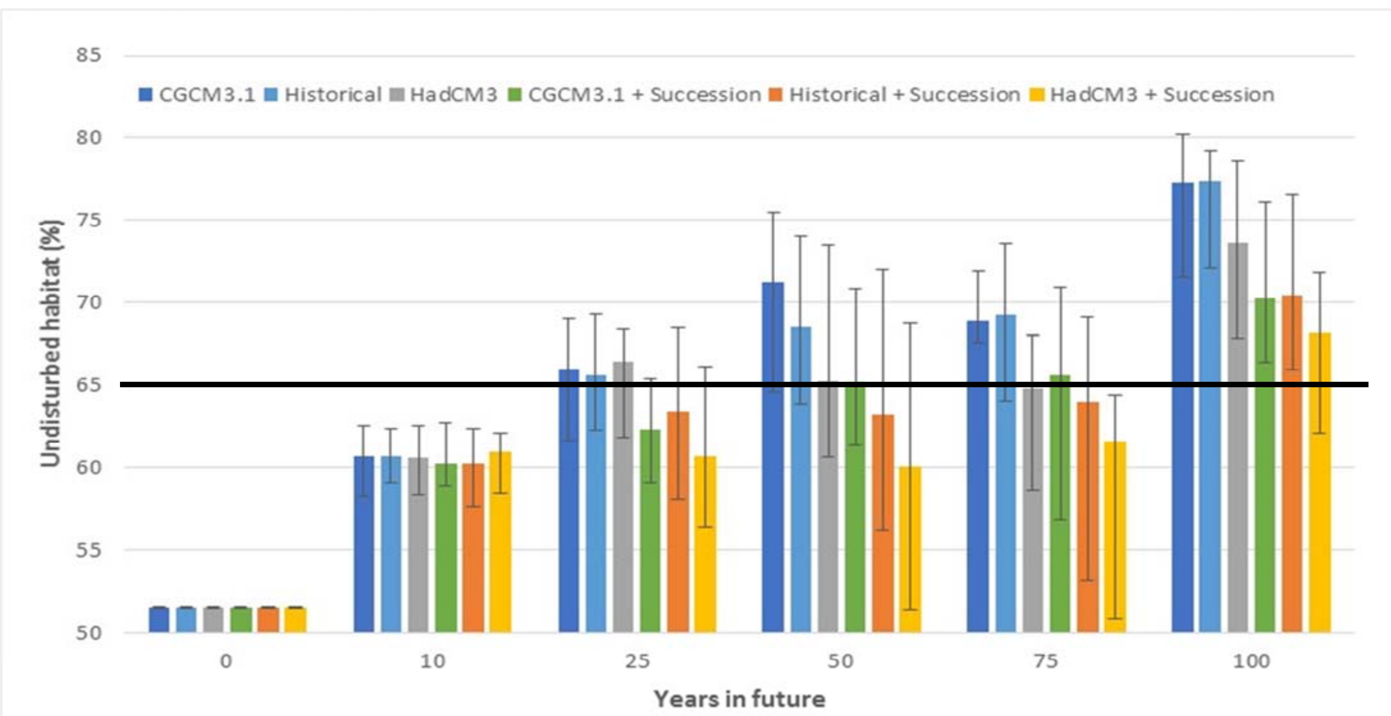
Table 24. Timber Harvest/Fire Scenarios*

		Fire Scenario	
Scenario*	**Logging scenario**	**Climate Projection**	**Succession Assumption**
1	Timber harvest	Historical	No Succession
2	Timber harvest	Historical	Succession
3	Timber harvest	HadCM3	No Succession
4	Timber harvest	HadCM3	Succession
5	Timber harvest	CGCM3.1	No Succession
6	Timber harvest	CGCM3.1	Succession
7	No timber harvest	Historical	No Succession
8	No timber harvest	Historical	Succession
9	No timber harvest	HadCM3	No Succession
10	No timber harvest	HadCM3	Succession
11	No timber harvest	CGCM3.1	No Succession
12	No timber harvest	CGCM3.1	Succession

**The succession model includes recolonization; all scenarios use 50-year fuel recovery. Fire scenarios are defined by combinations of climate projections and succession assumptions.*

Currently (2015), 52% of the study area is in an undisturbed condition (Figure 64). Undisturbed range generally increases over the next 100 years. A substantial increase occurs between year zero and 25, due to recovery of seismic lines and historical fires, with a smaller increase between years 75 and 100. The stability of the increase between year 75 and 100 is unclear without examining results for a longer time frame.

Figure 64. Median Undisturbed Range Resulting from Different Fire Scenarios Defined in Table 23 (Year 0 = 2015)*; Timber Harvest and No Timber Harvest Scenario Results are Combined

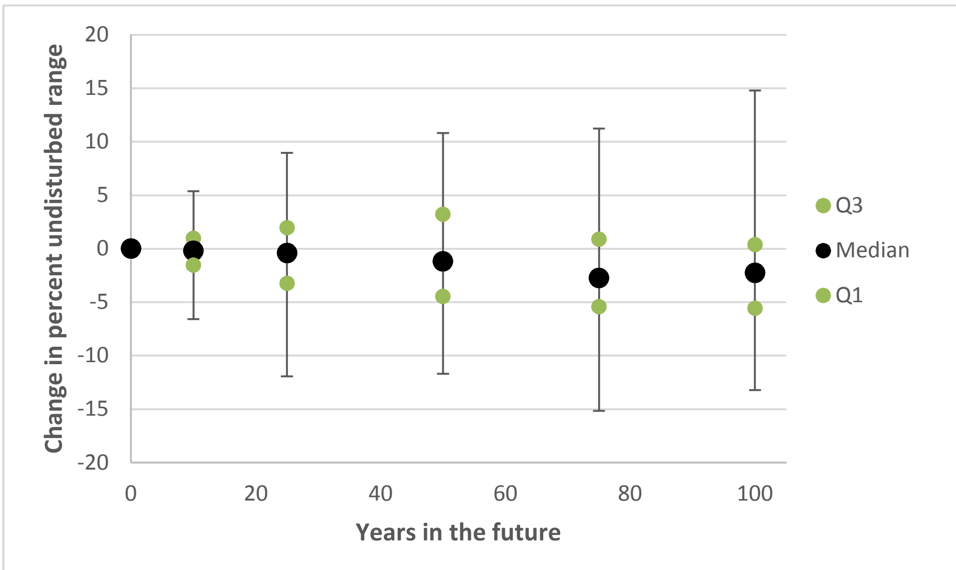


**Timber harvest and no-timber harvest results are combined for each sample year. Whiskers bracket the middle 50% of results. The black line highlights the 65% undisturbed habitat target.*

3.2.2.1 Effect of Timber Harvest on Undisturbed Range

The following section examines the influence of green-tree timber harvest versus no timber harvest across a range of six fire disturbance scenarios, each with ten replicates for a total of 120 simulations (Table 24). Harvest within the timber harvesting land base (~1 % of the study area) reduces the median amount of undisturbed range by two percent over the 100-year simulation (Figure 65). The median change in undisturbed range represents a very small portion of the total variability. The difference between timber harvest versus no timber harvest varied between -6% and +3%, half of the time (i.e., between the first and third quartiles). Variability increases with time.

Figure 65. Percent Change in Undisturbed Range Due to Timber Harvest (Year 0 = 2015)*



** The markers show median and the first (Q1) and third (Q3) quartiles. The whiskers show the full range of results.*

3.2.2.2 Effect of Fire on Undisturbed Range

Due to the relatively small effect of harvest, the twelve scenarios (Table 24) were collapsed to six by combining timber harvest and no-timber harvest results; hence each fire disturbance scenario had twenty replicates. For most of the next century (i.e., sample years 25, 50, 75), median range values from different scenarios bracket the 65% undisturbed range target (Figure 64). All scenarios have at least a 25% chance of failing to meet the habitat target prior to year 100 (the lower whiskers in Figure 64), with the exception of CGCM3.1 in year 75. For climate change models without succession, the median 65% undisturbed range condition will be achieved sometime between 10 and 25 years from now. Including succession, the median 65% undisturbed range condition will not be achieved until between 25 and 50 years from now for the CGCM3.1 + Succession scenario, and between 75 and 100 years from now for the Historical + Succession and HadCM3 + Succession scenarios. All scenarios show substantial variability.

Climate projections and succession assumptions affect undisturbed range availability. The relatively hotter and drier HadCM3 climate projections leave less habitat than historical or CGCM3.1 climates. Historical and CGCM3.1 climate projections produce similar results. Scenarios with succession leave less habitat than their counterparts without succession, due to rapid successional transition from deciduous to more flammable conifer species and hence increased fire disturbance.

Most habitat occurs in patches exceeding 500 km^2 (figures 66 to 68). Fire disturbance, without timber harvest, leaves less than 5% of habitat in patches of less than 500 km^2 after year 25 (Figure 69). Timber harvest reduces the percentage of large patches by 1 to 2%.

Undisturbed range calculations are sensitive to assumptions about habitat recovery period. Results presented above are based on a 40-year recovery period. Including a regeneration delay extends recovery. Extending the period to 60 and 80 years decreases median range abundance by about 13% and 20% respectively, putting median range at or below 65% for all scenarios. Note that because fires were not recorded prior to 1950, undisturbed habitat may be underestimated during the first 15 years of simulation (i.e., prior to 2030) when using the 80-year recovery assumption.

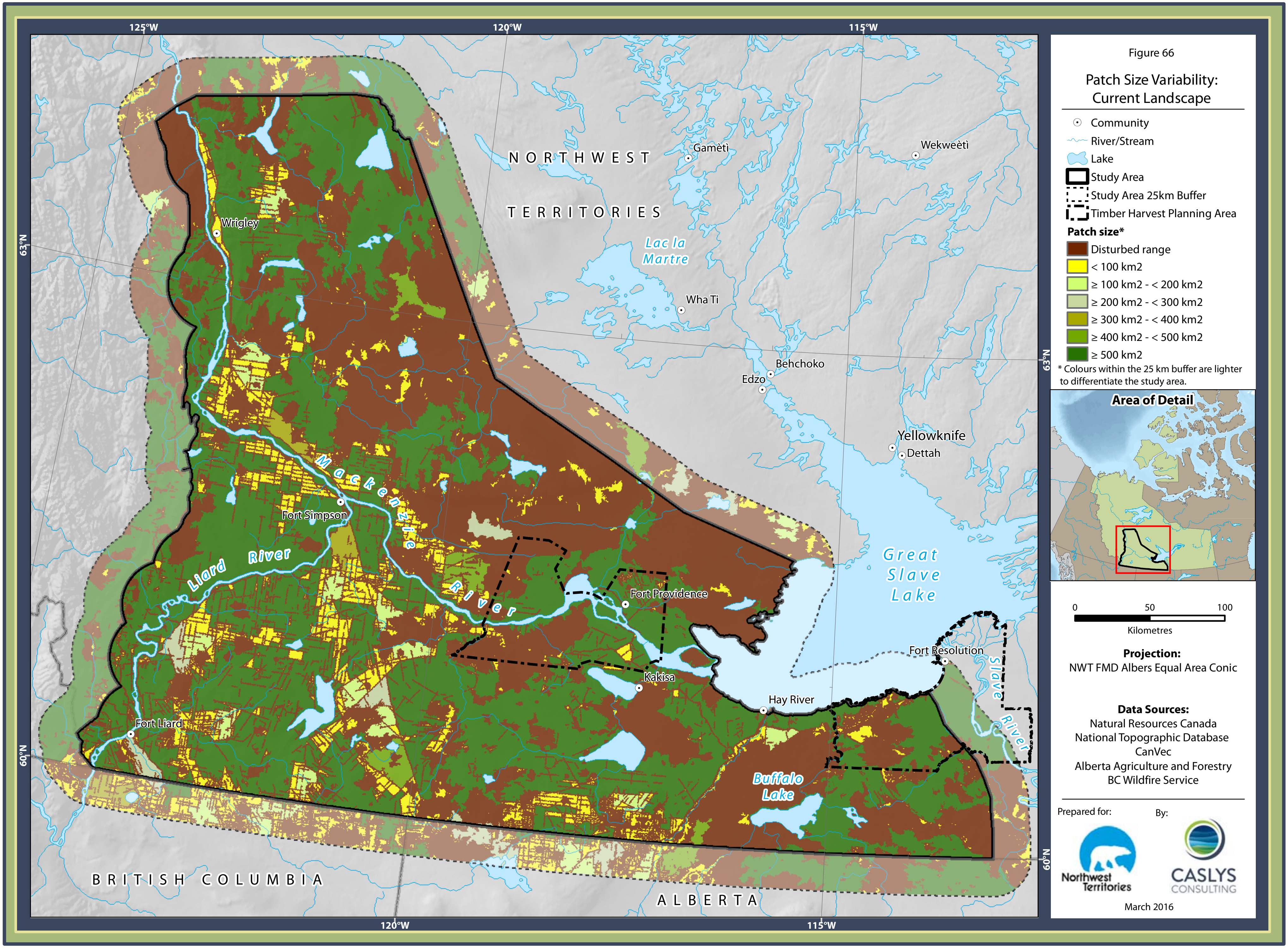


Figure 66
Patch Size Variability: Current Landscape
Community
River/Stream
Lake
Study Area
Study Area 25km Buffer
Timber Harvest Planning Area
Patch size*
Disturbed range
< 100 km2
≥ 100 km2 - < 200 km2
≥ 200 km2 - < 300 km2
≥ 300 km2 - < 400 km2
≥ 400 km2 - < 500 km2
≥ 500 km2
* Colours within the 25 km buffer are lighter to differentiate the study area.
Area of Detail
0
50
100
Kilometres
Projection:
NWT FMD Albers Equal Area Conic
Data Sources:
Natural Resources Canada
National Topographic Database
CanVec
Alberta Agriculture and Forestry
BC Wildfire Service
Prepared for:
By:
Northwest Territories
CASLYS CONSULTING
March 2016
125°W
120°W
115°W
63°N
60°N
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
Gamètì
Wekweètì
Wrigley
Lac la Martre
Wha Ti
Behchoko
Edzo
Yellowknife
Dettah
Mackenzie River
Fort Simpson
Liard River
Fort Providence
Great Slave Lake
Fort Resolution
Slave River
Kakisa
Hay River
Fort Liard
Buffalo Lake

Figure 67. Examples of Patch Size Variability: 50 Years in the Future - Replicates A and B of Ten Replicate Simulations Examining Timber Harvest with No Succession using the CGCM3.1 Climate Model

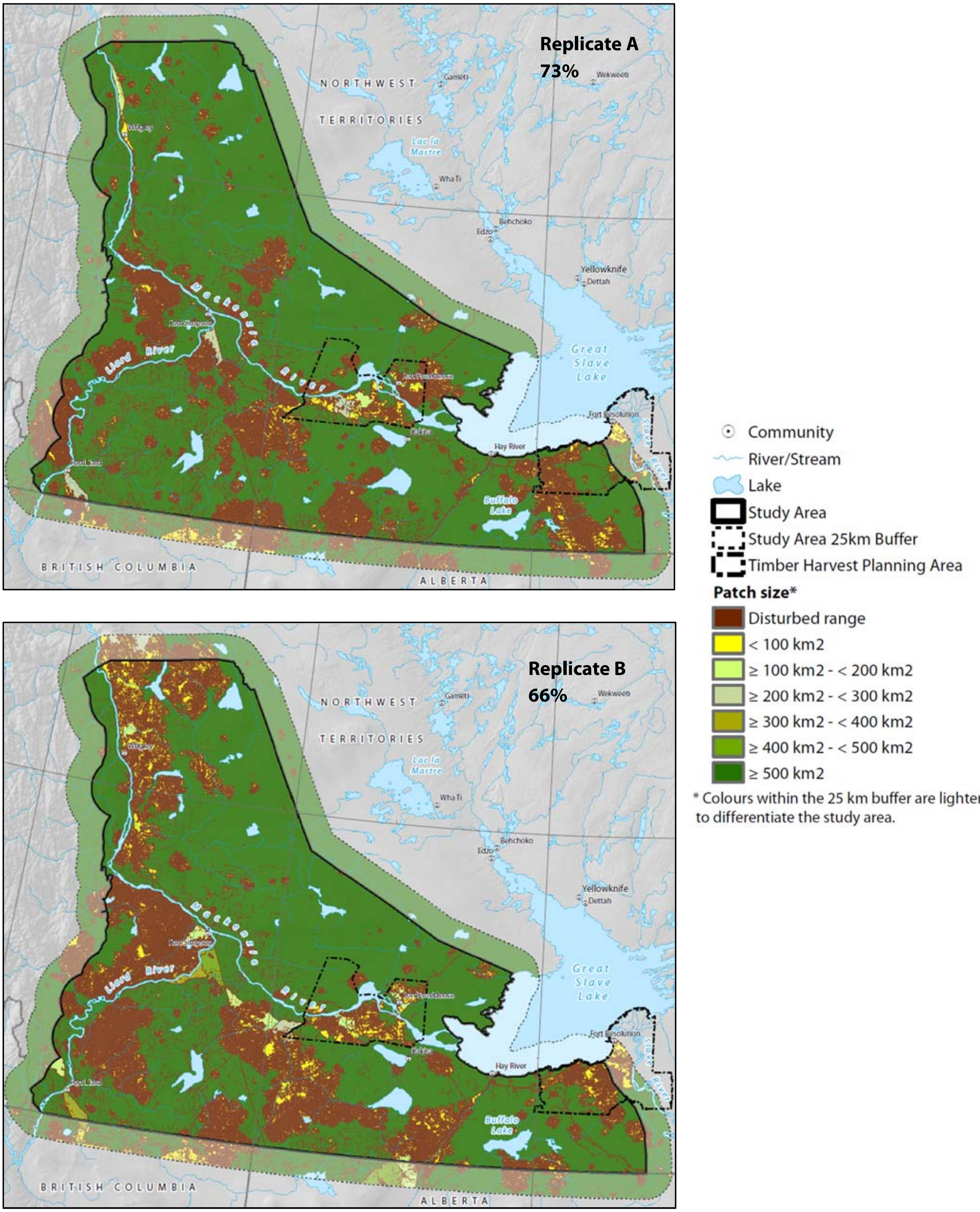


Figure 68. Examples of Patch Size Variability: 100 Years in the Future - Replicates A and B of Ten Replicate Simulations Examining Timber Harvest with No Succession using the CGCM3.1 Climate Model

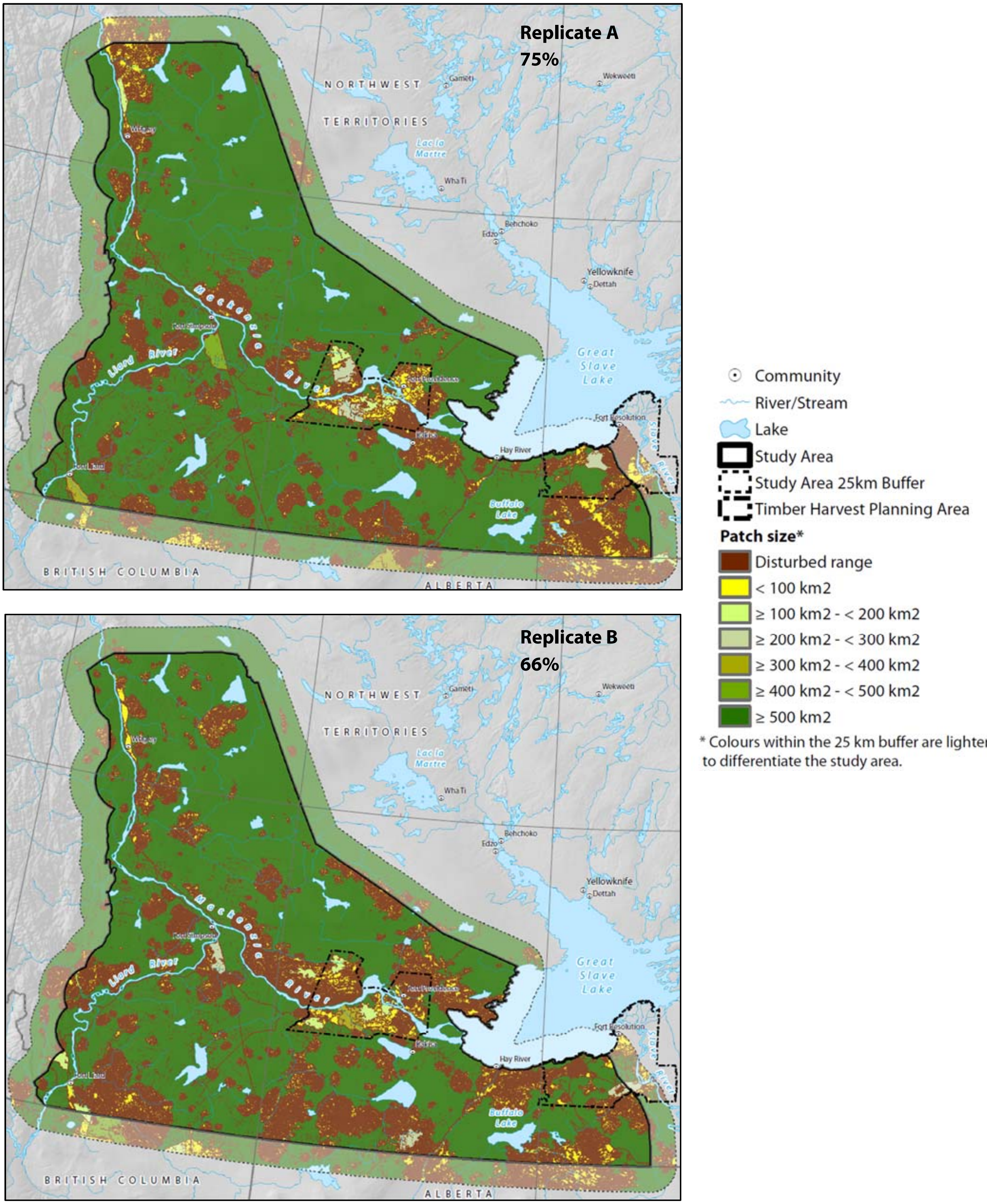
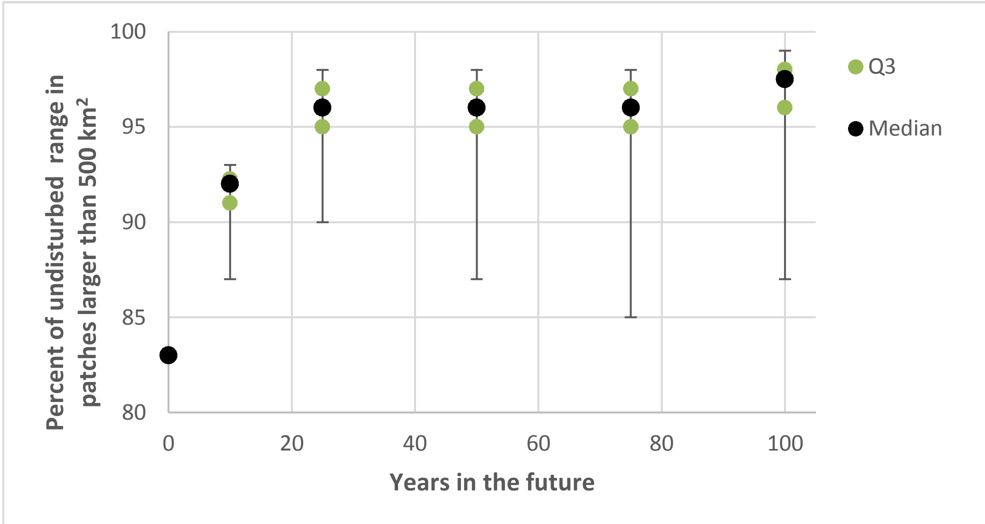


Figure 69. Percent of Undisturbed Range in Patches Larger than 500 km^2 for Selected Years (Year 0 = 2015)*

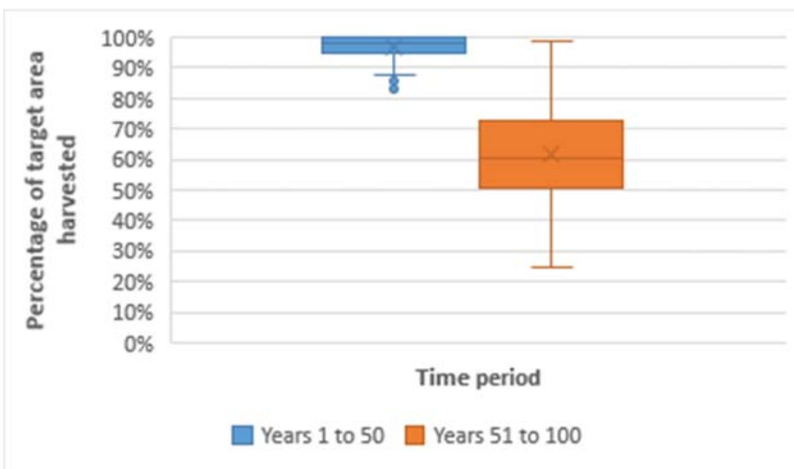


**Results for six fire scenarios with no timber harvest. The markers show median and quartiles; the whiskers show the full range of results.*

3.2.2.3 Effect of Fire and Caribou Constraints on Annual Timber Harvest

Projected fire disturbance has a minor effect on timber harvesting over the next 50 years. Harvested area declines to 60% (median) of the specified target between 50 and 100 years (Figure 70), however, as fires affect the forest management areas (Figure 71), variability is high; some simulations achieved the target, others achieved only one quarter of the target, likely reflecting high variability in fire location and area burned. Three quarters of the simulations achieved more than 50% of the harvest target in the latter time period (years 51 to 100). Salvage harvesting was not simulated but is expected to mitigate impacts.

Figure 70. Percentage of Harvest Target that was Harvested by Time Period*



**Across all scenarios including timber harvest. The mean is represented by 'X'. The horizontal line within the boxplot shows the median. The bottom and top of the boxplots show the first and third quartiles respectively. The whiskers show the full range of results.*

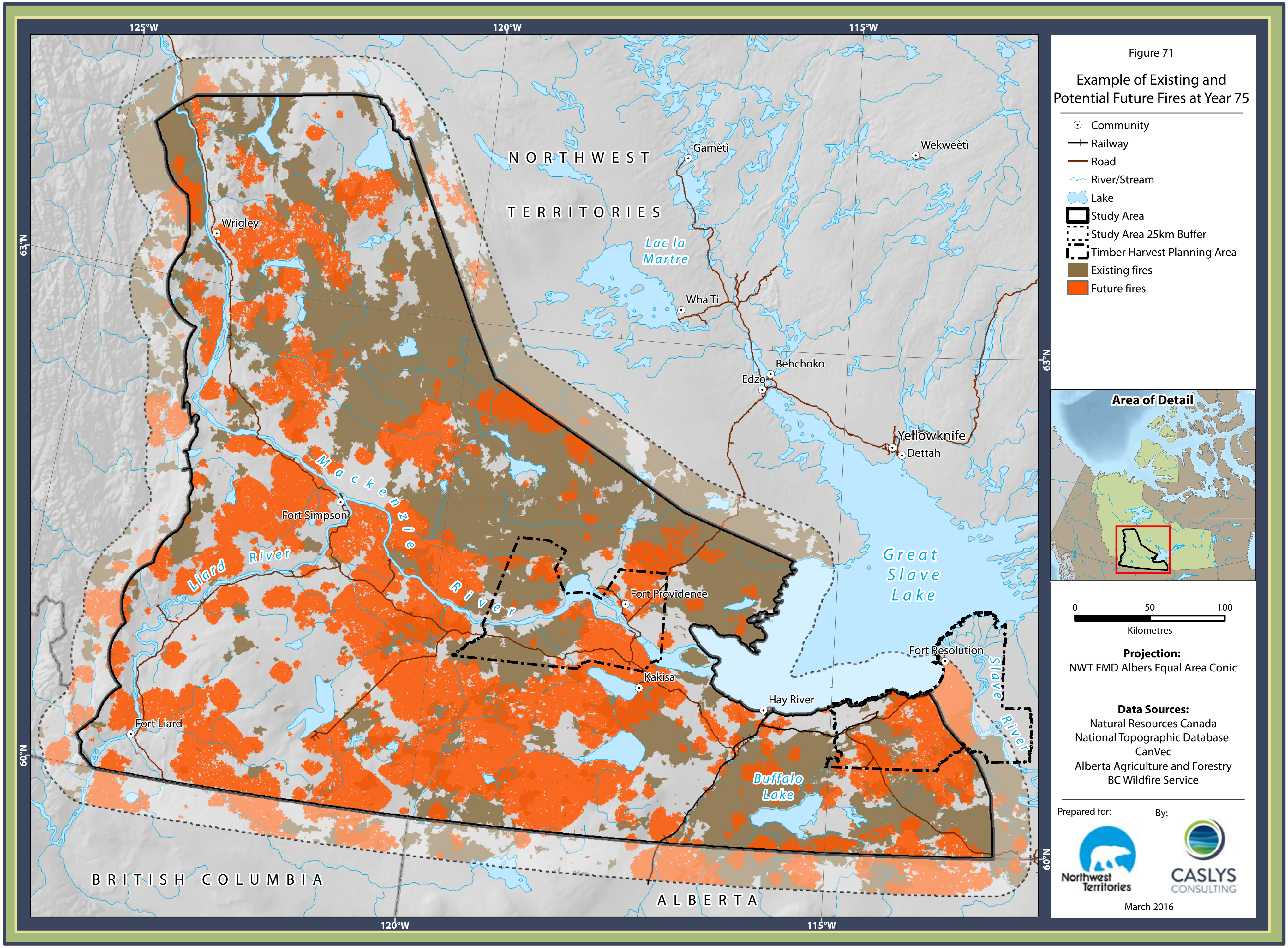


Figure 71

Example of Existing and Potential Future Fires at Year 75

Habitat-disturbance constraints have about a 50% chance of influencing timber harvest activity over the middle portion of the next 100 years (Table 25). Enforcement of constraints would not allow harvest for more than a decade from 2015. Annual harvest targets were not constrained in the model when caribou habitat fell below 65%; hence harvest levels are optimistic (see Section 3.2.1.2).

Table 25. Percent of all 120 Simulations, with and without Timber Harvest, Where Undisturbed Habitat Exceeds 65% and Timber Harvest would be Unconstrained, for Selected Years

Year	0	10	25	50	75	100
Percent of simulations with more than 65% undisturbed habitat	0%	0%	46%	53%	53%	80%

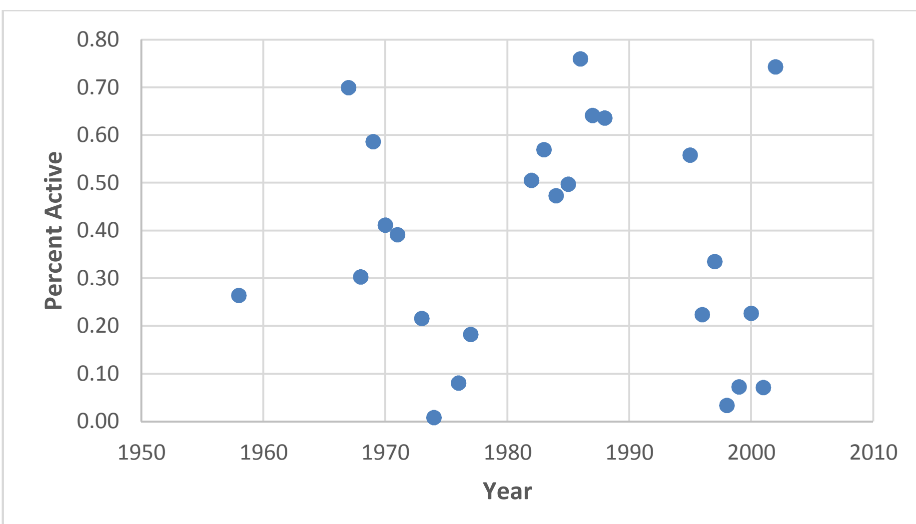
3.3 Restoration Status

For the purpose of this project, additional examination of linear feature datasets with reference to disturbance dates and land cover was also conducted. Linear datasets used in the restoration status analysis included the Environment Canada linear feature dataset and the NEB seismic line dataset, which were both compared to the EOSD Integrated Land Cover dataset and NWT FRI land cover dataset.

Given that the EC linear features are considered active disturbances on the land (as of 2010), linear features that were not present in the dataset but present in the NEB seismic line dataset were considered recovered. It is known that disturbance features in upland habitat areas recover faster than those in wetland habitat areas (van Rensen et al., 2015), therefore particular attention was made in comparing the active and regenerated linear features with land position (e.g., upland, wetland).

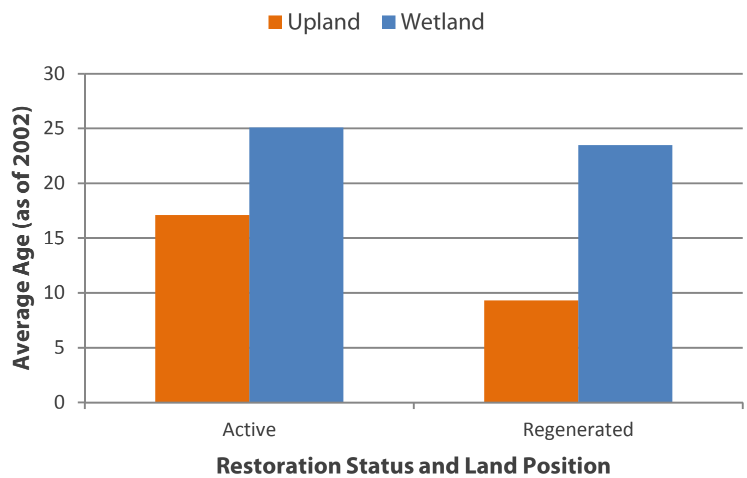
The results of the restoration analysis showed very little correlation between seismic line recovery and time since disturbance. Figure 72 shows the proportion of NEB seismic lines that are considered active, or are present in the 2010 EC linear feature dataset (i.e., visible in imagery). There is little to no correlation between seismic line recovery status (i.e., active versus recovered) and disturbance date. Between 1980 and 2000, seismic lines became narrower and used less destructive technology, although there appears to be no correlation between seismic line status and disturbance date after this time.

Figure 72. Recovery Status by Disturbance Year for NEB Seismic Lines



For the NEB seismic lines, it was found that while there was no strong correlation between cut date and recovery status, results showed a weak correlation between land position and recovery status (Figure 73). That is, NEB seismic lines in wetland areas were older, on average, than lines in upland areas, for active and regenerated lines. Comparing the same parameters on the EC linear dataset did not yield a strong correlation. This corresponds to the findings discussed above, where there was found to be poor or no recovery in wet lowland areas (Seccombe-Hett and Walker-Larsen, 2004; Lee and Boutin, 2006; Bayne et al., 2011, van Rensen et al., 2015; Kansas et al., 2015).

Figure 73. Average Line Age by Restoration Status and Land Position for NEB Seismic Lines



4.0 DISCUSSION

Caribou are sensitive to natural and anthropogenic disturbance. The Boreal Caribou Recovery Strategy identifies critical habitat as 65% of the range in an undisturbed condition.

4.1 Current Boreal Caribou Range Status

Currently, undisturbed caribou range covers about half (52%) of the study area. Fire disturbance has had the greatest influence on undisturbed caribou range to date. By 2011, fires within the previous 40 years had reduced undisturbed range to 69% of the study area. Between 2011 and 2015, large fires further reduced the amount of range unburned within 40 years to 62% of the study area. Existing linear and areal anthropogenic disturbances further reduce undisturbed range. These features, with 500 metre buffers, disturb approximately 15% of the study area when considered alone. Accounting for the overlap of fires and anthropogenic features leaves 52% of the range undisturbed.

Many existing anthropogenic features (e.g., settlement, mines, gas wells, roads, powerlines) are considered to be relatively permanent and thus create a stable disturbance footprint over the simulation period. Permanent areal features cover a very small portion of the study area (about 0.1%). Permanent linear features also have a relatively small footprint, even when buffered by 500 metres either side (2 – 3% of the study area). The existing approximately 25,000 km of seismic lines have the largest anthropogenic disturbance footprint (about 12% of the study area), but these disturbances have the potential to recover their habitat value over time.

The simulation model projects the ongoing influence of fire, anthropogenic disturbance and vegetation recovery on the amount of undisturbed range and undisturbed patch size for 100 years into the future.

4.2 Projected Anthropogenic Disturbance and Recovery

As only approximately 1% of the study area is currently available for forest harvesting (7.1% of the study area lies within the two THP areas but only a portion of those THP areas are merchantable timber), the contribution of forest harvesting to range disturbance over the entire study area is low, increasing disturbed range by about 2% over the next 100 years. Expansion of forestry activities within the entire study area would cause more substantial disturbance, as forest harvesting creates high levels of disturbance per unit area. For example, in a simulation within the Fort Providence FMA boundary, forest harvesting alone reduced undisturbed range to about 60% and reduced large undisturbed patches (> 500 km^2) to almost 40%. Buffers around cutblocks and access roads make the impact of forest harvesting higher than the impact of fire per unit of area disturbed, particularly given that the relatively dispersed, patchy distribution of merchantable timber tends to spread harvesting activity across a larger area.

Most existing seismic lines (about 80%) are expected to recover within 50 years, reducing range disturbance by roughly 10% over this period. Remaining seismic lines are projected to recover more slowly. Connectivity among patches of undisturbed range improves substantially over about 25 years as sections of seismic lines recover. Consequently, the proportion of range in patches greater than 500 km^2 also increases, although small breaks in the linear disturbance may not reduce overall predation risk associated with the longer, unrecovered portions of the linear features.

4.3 Projected Fire Disturbance

Fire is the dominant disturbance on the landscape and currently the main cause of disturbance to caribou range. As recent fire disturbance demonstrates, fire alone can push undisturbed range below 65%. The future fire regime will drive risk to boreal caribou range over this century.

Flannigan et al. (2005) estimated that area burned in the taiga plains, an ecoregion that largely coincides with boreal caribou range in NWT, would increase by 1.25 to 1.5 times using climate projections from the Canadian Coupled General Circulation Model (CGCM1) and by 1.5 to 2 times using climate projections from the Hadley General Circulation Model (HadCM3). The broad result of higher area burned for the Hadley than the CGCM model matches our finding for the study area, although our projected area burned is lower in both cases. While predicting the future is not possible, CGCM3.1 projections better match ensemble projections, combining results from multiple models and emissions scenarios, than do Hadley projections. Both our study and Flannigan et al. (2005) assumed that carbon-dioxide emissions would be near the high end of projected emissions scenarios—an assumption supported by recent emission trends. Moderate emissions assumptions do not substantially alter mid-century climate projections. Unlike our study, Flannigan et al. (2005) do not include likely compensatory feedbacks related to fuel recovery, which may account partially for their higher overall projected burn rate.

Unfortunately, accurately predicting fire disturbance is hampered by two types of uncertainty: 1) limited knowledge about the fire regime and 2) stochastic variability in fire location and weather patterns. Increased knowledge can reduce the first type, but not the second type, of uncertainty. The following section describes three sources of somewhat resolvable uncertainty: baseline annual burn rates, future climate, and recovery of fuel flammability following disturbance.

Baseline annual burn rates: Estimates of mean area burned annually due to the historical fire regime vary from approximately 0.6 to 1.2%/year by region and with different methods (Table 3, Section 1.3.3.1). Actual historical burn patterns provide a poor baseline because they represent a single example of a pattern driven by stochastic events. As a baseline, the fire model was calibrated to burn about 0.9%/year on the 2011 landscape, an amount lying within the range suggested by historical data and the Burn-P3 model results. Hence, uncertainty around the estimated historical mean annual burn rate is +/- 33% (i.e., 0.6%/0.9% to 0.9%/1.2%).

Variation in baseline annual burn rate changes undisturbed range considerably. For example, based on a negative exponential fire model (random fire locations with immediate recovery of fuel flammability; Johnson and Gutsell, 1994) a 0.8%/year burn rate, as calculated for the Dehcho region, would leave 73% undisturbed range, while a 1.2%/year burn rate, as calculated for the South Slave region, would leave 62% undisturbed range. The model did not explore the impacts of changes in baseline burn rate.

Future Climate: In our models, area burned is projected using climate projections and historical weather data. Climate models vary substantially in their predictions of summer temperature and precipitation, and consequently in their predictions of area burned: the wetter CGCM3.1 model leads to decreased annual burn, while the hotter and drier HadCM3 model increases burn rate over time (Table 26). Modelled burn area is influenced by uncertainty in both fire and climate models. Uncertainty related to climate projections related to percent of baseline burn ranges from -11% (CGCM3.1 2080) to +24% (HadCM3 2080) by 2080 (Table 26).

Table 26. Estimated Area Burned for Different Projected Climate Conditions from Burn-P3

	Baseline (Model)	HadCM3 2050	HadCM3 2080	CGCM3.1 2050	CGCM3.1 2080
Midpoint of 30-year period	1990	2050	2080	2050	2080
Mean annual burn (%/year)	0.85	1.03	1.05	0.81	0.76
Percent of baseline burn (%)*	100	121	124	95	89
Percent > 40 years (%)	71	66	66	72	74
Return interval (years)	118	97	95	123	132

**Future model's area burned divided by baseline model's area burned.*

Recovery of fuel flammability following disturbance: Fuel recovery assumptions also influence fire behaviour, and hence annual burn rate, substantially. The model includes location-specific spread rates, based on Burn-P3 results, and vegetation succession and growth. Following disturbance, stands have a higher chance of recolonizing with less-flammable deciduous species; over time, the deciduous component declines and the more flammable conifer component increases. The rate of transition from deciduous to coniferous species influences annual burn; rapid transition to flammable conifer species increases percent annual burn rates by 10% relative to slower transition rates. Similarly, rapid revegetation and growth on disturbed sites increases fuel flammability; immediate fuel recovery increases annual burn by 10% relative to a 50-year gradual recovery of flammability. Together, assumptions about recovery rate and succession account for 20% uncertainty (+/- 10% around a midpoint).

In summary, uncertainty about the historical disturbance rate could shift the projected burn rate by +/- 33%, uncertainty about climate change could shift the rate from -11% to +24%, and uncertainty about fuel recovery could add another +/- 10%. **Overall, uncertainty about projected fire disturbance is high, with estimated means potentially ranging from -54% to +67% of the modelled midpoint leading to a change in boreal caribou range of approximately +/- 15%.**

4.4 Range Recovery Period

Analyses conducted to support the boreal caribou Recovery Strategy found a good correlation between a time since fire of less than 40 years and caribou population status. Hence, the model assumes cutblocks recover their range value after 40 years. This is consistent with the length of time for recovery following fire used in the Recovery Strategy (Environment Canada, 2012). The Recovery Strategy analyses, however, included caribou populations across Canada and may not be entirely applicable to the NWT population. In particular, vegetation in the NWT recovers more slowly than vegetation in more southerly populations. Research within the study area suggests a regeneration lag of up to 50 years (lag estimates provided by GNWT), lengthening (potentially doubling) the forest recovery period. Modelling found that regeneration delays increase the area of disturbed range, as expected, but that the increase was not directly proportional because disturbances overlap. For example, doubling recovery time from 40 to 80 years increased disturbed range by 20%.

There are other challenges involved in applying the Recovery Strategy analyses to the NWT. Analyses supporting the boreal caribou Recovery Strategy defined recovery periods for anthropogenic features based on their visibility on satellite imagery. This approach works with past disturbance but does not allow projection of future recovery without correlating recovery time to visibility. Our attempt to correlate seismic line visibility with their dates of origin, for a subset of seismic line data, failed to generate a recovery relationship.

4.5 Implications to Boreal Caribou

4.5.1 Percent Undisturbed Range

Currently, 52% of the study area is in an undisturbed condition, which is below the Recovery Strategy's 65% undisturbed minimum threshold for critical habitat for boreal caribou ranges. The dominant disturbance in the study area is fire, which covers 38% of the study area (including 7% burned in the five years since 2011), followed by seismic lines (about 12% of the study area), and other anthropogenic features (2 – 3% of the study area). Note that some disturbances overlap.

The current area of undisturbed range is lower than Environment Canada's calculation of 69% for the whole NWT Boreal Caribou range for two reasons. First, the study area includes only the Dehcho and South Slave portions of the NWT Boreal Caribou range, which contain higher levels of habitat alteration than the northern part of the range (Nagy, 2011; Species at Risk Committee, 2012). Second, the undisturbed range level was calculated based on disturbance levels existing in 2010 (Environment Canada, 2012) and hence excludes the large fires that burned between 2011 and 2015. Recent updates to range statistics that account for new fires indicate 66% undisturbed range (James Hodson pers. comm.) across the whole NWT boreal caribou range but this estimate does not account for small amounts of new human disturbance and recovery of existing human disturbance.

Applying analyses completed at one scale to another scale can be fraught with challenges if underlying variability is high. While the analyses that supported the Recovery Strategy were conducted at an appropriate scale for a federal assessment, the results may need to be refined and calibrated for application at smaller scales. Two variables are particularly relevant to analyses for the NWT: regeneration delay and type of disturbance. The Recovery Strategy used 40 years for recovery of boreal caribou range following fire. However, in NWT, ecological recovery and growth rates are very slow, and forests experience a regeneration delay of up to 50 years (Table 8). When delayed regeneration is modelled, it reduces undisturbed range considerably: a 20-year delay reduces undisturbed range by 13%; a 40-year delay reduces it by about 20%. **Hence, analyses that do not consider regeneration delay in NWT may be overly optimistic.** NWT disturbance types could counteract this effect, however. The Recovery Strategy combined anthropogenic and natural disturbances to examine overall impacts over a vast area. However, natural disturbances, which do not include roads and other linear features associated with anthropogenic disturbances, may pose lower risk to caribou. Large fires also have relatively less edge habitat (favoured by other prey species) per hectare burned. If natural disturbances have lower impact, **the primarily fire-disturbed habitat in the NWT may reduce functional habitat less than anthropogenic disturbances**. Current data are insufficient to calibrate models for this assessment.

4.5.2 Undisturbed Patches

Patches >500 km^2 currently comprise 83% of the undisturbed area. This amount differs considerably from calculations reported by Nagy (2011): 15.2%, 46% and 13.8% secure unburned habitat for the South Slave, Dehcho-north and Dehcho-south study areas, respectively. The discrepancy can be attributed to different input data sources and parameters between the two studies. To assess whether undisturbed range exceeded the 65% threshold determined in the Recovery Strategy, we deliberately used the same data sources and parameters that were used in the Recovery Strategy including a) Environment Canada disturbance mapping, b) 500 metre buffer around anthropogenic disturbance, and c) fire disturbance within 40 years. Nagy (2011) used a) the National Energy Board database as the primary source for anthropogenic disturbance mapping, b) a 400 metre buffer around anthropogenic disturbance, and c) fire disturbance within 51 years (1957 to 2008). Although a 400 metre versus a 500 metre buffer should result in more large undisturbed patches, the considerable difference in seismic lines between the two data sources eclipsed that effect. Early in our analyses, we assessed this difference in a portion of the study area; we found that the NEB database contained far more seismic lines than

Environment Canada's disturbance mapping. Also, because Environment Canada's disturbance mapping only included disturbances that were visible on 1:50,000 Landsat imagery, seismic lines were broken up in areas where the line was no longer visible, whereas the NEB database contained entire line lengths. Breaking up disturbed portions of the seismic lines with as little as 1,250 metre (250 metre pixel size + 500 metre buffer on each side) of undisturbed habitat resulted in connecting polygons on either side of the seismic line, and in larger overall polygon size despite a potentially 'hour-glass' shape. If these breaks in seismic lines are small and rare, the probability of caribou using them will be low and caribou will continue to primarily cross the unrecovered portions of the seismic lines where mortality risk is higher.

Due to the different disturbance layers and buffer distances used in our analyses, we are unable to assess whether Nagy's (2011) recommended "≥ 46% of the area in secure unburned habitat (i.e., >400 metres from seismic lines) and 54% of that secure unburned habitat in patches >500 km^2", was achieved in our model runs[7]. Although we were unable to assess the absolute amount of large undisturbed patches against Nagy's (2011) threshold, we found that the area of patches >500 km^2 increased over time. This increase was primarily due to recovery of portions of seismic lines together with the assumption of no new seismic lines. Again, undisturbed patch size could potentially jump substantially when two polygons were connected after a small portion of a seismic line achieved recovery. **When assessing undisturbed range following recovery of disturbed habitat, especially in cases where only portions of seismic lines recover, a combination of patch size and patch shape may provide a better representation of functionally undisturbed range than patch size alone.**

4.6 Limitations

The following limitations are associated with the source data and results:

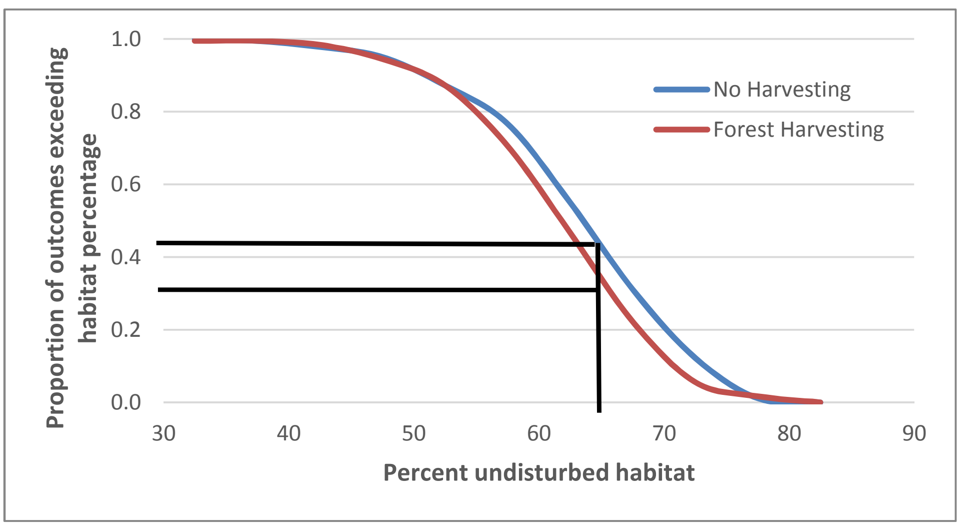
- Examination of future anthropogenic disturbance was limited to planned timber harvest. The model did not examine expanded forest harvesting activity (i.e., outside the THPs), increased exploration and seismic activity or increased settlement. Increased anthropogenic disturbance would decrease the amount of undisturbed range and patch size.
- The simulations did not fully explore different assumptions about baseline historical burn rates, but focussed on the effects of climate change and vegetation succession and recovery on burn rates. Future work could explore the effects of differences in baseline burn rates, although existing simulations provide a reasonable range of variability.
- The influence of vegetation recovery and succession on fuel flammability would benefit from better understanding and calibration, however the information needed does is not currently available in NWT.
- Existing fire data do not identify unburned or partially-burned patches within the fire perimeter, which account for about 5% to 50% of the fire area, respectively (Bergeron et al. 2002; Eberhart and Woodward 1987). The caribou habitat value of partially-burned patches of forest is not well established. The SELES fire module does not simulate partially-burned areas or count these areas as habitat. This approach is consistent with analyses used to support the boreal caribou recovery strategy that are based on fire perimeters. The SELES fire module does leave a small percentage of unburned patches within fires.
- NWT forest inventory is insufficient to assess stand age and land cover reliably within the study area. In particular coverage is not available for the full study area.

[7] The data used by Nagy (2011) contains substantially more seismic lines than the Environment Canada data set used to develop the Recovery Strategy. Analysis results may differ substantially because of data resolution and therefore direct comparison is inappropriate without a thorough analysis to quantify the effects of differences in datasets.

4.7 Decision-making in Uncertain Environments

In uncertain environments, it is often useful to consider the probability that alternative policy options will achieve desired outcomes. Resource management in NWT operates in an environment with high uncertainty, due both to historically high rates of fire disturbance and to a changing climate. Disturbance affects human-created infrastructure, timber resources and non-timber values including caribou range. Uncertainty about caribou range condition is high due to stochasticity and to uncertainty in mean annual burn rate (Section 4.3). Combining the scenarios of multiple plausible variables (Section 3.2.2) into a cumulative frequency distribution shows the likelihood of achieving a given target level of undisturbed range, and is hence a useful decision tool. Each replicate of each scenario provides a single estimate of undisturbed range; these estimates can be combined into a frequency distribution. Scenarios include three climate options (historical, HadCM3, CGCM3.1) and fuel recovery with and without succession for a total of six scenarios (Table 24). Each scenario was replicated ten times to capture stochasticity; hence there are 60 simulation runs included. The consistency in projected results between years 25 and 75 allow combination of these time periods into a single distribution based on 180 estimates covering a wide range of plausible scenarios. This period is sufficiently long to be useful for making management decisions about caribou. Projected undisturbed range estimates increase by year 100. Figure 74 excludes 100-year results for two reasons: combining inconsistent results is statistically unsound; and, the stability of this increase is uncertain without a longer simulation period. Even if certainty was greater that the level of undisturbed range increases by year 100, caribou will have been exposed to higher levels of disturbance, and therefore higher risks, for up to 100 years before they could benefit from increased levels of undisturbed range.

Figure 74. Cumulative Frequency Distribution of Undisturbed Range, Based on 180 Outcomes each for Forest Harvesting and No Harvesting*



**Outcomes include years 25, 50 and 75 in six fire scenarios with ten replicates each.*

Figure 74 shows cumulative distribution frequency curves for two policy options: with and without forest harvesting. The distribution frequency shows that no simulations project more than 75% undisturbed range and that 90% project more than 50% undisturbed range. The 65% caribou range target lies on the region of the highest rate-of-change in the curve, meaning that small changes in policy can have a relatively large influence on the probability of achieving a minimum undisturbed range target. **Although forest harvesting only reduces undisturbed range by a small amount in simulations (2%), this reduction lowers the probability of achieving or exceeding a minimum 65% target from 0.43 to 0.34** (Figure 74). Similarly, other types of development that leave a long-term footprint (e.g., roads and seismic lines) have a high potential to influence achievement of minimum targets. Given the importance of the shape of the cumulative frequency distribution for development decisions, reducing uncertainty about the effects of future fires on range may be important.

Climate change has the potential to increase or decrease, disturbance. Climate change also has the potential to alter vegetation recovery processes following disturbance. While tree growth is expected to increase with climate change, regeneration may be hampered, and mortality related to insects and disease will likely increase. Melting permafrost can inhibit vegetation growth. The net effect of climate change on range recovery for caribou is uncertain, as is the net effect on fuel recovery.

Given that natural disturbance levels, in the face of climate change and due to natural stochasticity, are uncertain and may pose high risk, management planning should consider cumulative impacts, particularly when managing landscapes that are approaching or over a disturbance threshold. Good management strategies to address uncertainty include those that are:

- **Precautionary:** avoid activities that increase risk,
- **Monitored:** assess natural and anthropogenic cumulative effects on a regular basis,
- **Responsive:** for example, following a high-fire year, harvesting level, and other anthropogenic disturbances, should potentially be lowered to avoid cumulative effects.

Formal adaptive management and research may also be useful to reduce uncertainty in some cases.

Analyses should be expanded to the remaining portion of the range so that management decisions can consider the entire NWT boreal caribou range. Minimum undisturbed range targets could potentially vary among sub-regions within the range (i.e., some subregions could have a lower proportion of undisturbed range, and hence pose a higher risk to caribou, while other regions compensate). Levels of acceptable risk should be established before conducting analyses to ensure science-based decision-making. Specifically, minimum undisturbed range targets for sub-regions should be determined by caribou biologists and should be based primarily on the needs of caribou rather than on range availability.

The Recovery Strategy identifies critical habitat as a **minimum** of 65% undisturbed range. At that level, there is a 60% probability that a caribou population will be self-sustaining. Higher levels of undisturbed range will result in a higher probability of maintaining a self-sustaining population (Environment Canada, 2012).

4.8 Recommended Future Work

Several studies could provide additional information to support decision-making related to boreal caribou:

- Engage caribou biologists to explore the potential to apply minimum undisturbed-range targets that vary among subregions within NWT boreal caribou range. Subject to caribou biology, a lower minimum target in the study area that is balanced by higher minimum targets within remaining range rather than a single minimum target applied across all subregions is one option for achieving a minimum of 65% undisturbed range across the whole range. Fire disturbance alone can prevent achievement of a 65% minimum target in the study area. For example, achieving 55% undisturbed range in the study area by mid-century, however, is more likely than not.
- Estimate future disturbance in other subregions of NWT boreal caribou range to support range-wide planning.

- Develop a long-term research/monitoring strategy to examine the effects of fire and anthropogenic disturbance on boreal caribou population dynamics. This should include further examination of the relative influence of different disturbance types (e.g., fire, linear features, industrial activities) within the boreal caribou range.
- Develop a research/monitoring program to examine ecosystem recovery following fire and anthropogenic disturbance. Knowledge of recolonization, growth and succession following disturbance is necessary to estimate rates of recovery of boreal caribou habitat and forest fuel flammability. Disturbance size and intensity, and site moisture and nutrient conditions, may all influence recovery. Climate change, particularly loss of permafrost, will also affect recovery.
- Work with climate researchers to establish a long-term weather monitoring network across boreal caribou range. Trends in precipitation and temperature can be used identify climate models that may be more applicable to boreal caribou range.
- Develop a land cover map that would allow a more up-to-date fuels layer to be derived. In addition, land cover mapping would allow the impact of fire disturbance to be quantified more accurately (i.e., unburned areas within fire polygons could be identified) and it would contribute to a better understanding of recovery rates.

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Appendix A

Data Structure Documentation

Table A-1 outlines the digital files from the Burn-P3 burn probability analysis that have been included with the report. They are provided in Esri grid format and are compatible with ArcGIS 10.x software.

Table A-1. Burn-P3 Burn Probability Models

Type	File Name	Description
Baseline Burn Probability (2015)	BaseActual	This scenario utilized the fuel and weather data as it existed in the fall of 2015 and therefore generated the burn probabilities over the landscape based on the current conditions within the study area.
Baseline Burn Probability (Model)	BaseModel	A model-derived baseline used for the climate change scenarios.
CGCM3.1 Climate Change Scenario (2050)	CGCM2050	Burn probability using the Canadian Center for Climate Modelling and Analysis (CGCM3.1) climate change scenario (2031 – 2060).
CGCM3.1 Climate Change Scenario (2080)	CGCM2080	Burn probability using the Canadian Center for Climate Modelling and Analysis (CGCM3.1) climate change scenario (2061 – 2090).
HadCM3 Climate Change Scenario (2050)	HAD2050	Burn probability using the Hadley Centre for Climate Prediction (HadCM3) climate change scenario (2031 – 2060).
HadCM3 Climate Change Scenario (2080)	HAD2080	Burn probability using the Hadley Centre for Climate Prediction (HadCM3) climate change scenario (2061 – 2090).

The following table (Table A-2) outlines the attributes included in each of the Burn-P3 burn probability grids.

Table A-2. Burn-P3 Burn Probability Attribute Fields

Field Name	Data Type	Length	Description
RowID	Float	n/a	An automatically generated ID field.
Value	Float	n/a	The burn probability percent value.
Count	Float	n/a	The number of cells which contain the burn probability percent value.

Appendix B

Burn-P3 Report

NWT (2015) BURN-P3 ANALYSIS IN SUPPORT OF LANDSCAPE PROJECTIONS ON BOREAL CARIBOU HABITAT PROJECT

March 31, 2016

Submitted by

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ACKNOWLEDGMENTS

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With thanks to NWT Government Employees:

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And special thanks to the following fire and climate change scientists:

- Marc-André Parisien, Fire Research Scientist, Northern Forestry Centre, Can. Forest Service, Edmonton AB.
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- Mike Flannigan, Professor of Wildland Fire, University of Alberta, Edmonton AB

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 purpose of this report is to describe the methodology and results of the Burn-P3 analysis completed in support of the project and report entitled 'Landscape Projections on Boreal Caribou Habitat' submitted to the Government of the Northwest Territory (GNWT) by Caslys Consulting Inc. (March 31, 2016).

A total of six Burn-P3 scenarios were completed:

1. Baseline (2015)

   Climate Change Scenarios
2. Baseline (model)
3. CGCM 2050
4. CGCM 2080
5. HAD 2050
6. HAD 2080

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

	Burn probability (%)					
Scenario	**Time Period**	**Average**	**99th Percentile**	**Maximum**	**Figure Number**	**Page**
Baseline (2015)	2015	0.59	2.78	3.76	10	20

Climate Change Scenarios	Time Period	Average	99th Percentile	Maximum	Figure Number	Page
Baseline (Model)	1981-2010	0.85	3.00	3.69	11	21
CGCM	2050	0.81	2.56	3.68	12	22
CGCM	2080	0.76	2.42	3.36	13	23
HAD	2050	1.03	3.21	4.38	14	24
HAD	2080	1.05	3.14	4.07	15	25

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INTRODUCTION

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 (Parisien et al., 2005). The Burn-P3 program utilizes Prometheus, the Canadian wildland fire growth simulation model (Tymstra et al. (2010), for all of the simulated fire growth calculations

To meet Federal Recovery Strategy objectives, the Government of the Northwest Territories, Environment and Natural Resources division (ENR) is developing a range management plan for boreal caribou. In support of the range management plan for the boreal caribou, a Burn-P3 analysis of the study area was required to quantify the current (2015) wildfire burn probability.

In addition to quantifying the wildfire burn probability as of the year 2015, the Burn-P3 program was used to estimate future burn probability based on potential fire weather conditions generated from two different climate change scenarios for two different future time periods.

The following Burn-P3 scenarios were run for this NWT study area:

1. **Baseline (2015)**
   - The Baseline (2015) scenario utilized the fuel and weather data as it existed in the fall of 2015 and generated burn probabilities over the landscape based on the current conditions within the study area. The fuel types used in the Baseline (2015) scenario were modified to take into account recent fire history; specifically, fuel types in areas of recent burns (<= 5 years) were re-classified to non-fuel and recent burns >5 and <10 years old were re-classified to a mixed-wood fuel type with a 25% conifer component (see Section entitled Fire Behaviour Prediction (FBP) Fuel Type Grids).

Climate Change Scenarios

2. **Baseline (Model)**
   - The Baseline (Model) scenario was generated as a baseline for all of the climate change scenarios. The fuel types for all of the climate change scenarios differ from the Baseline (2015) scenario fuel types in two ways. The climate change fuel types are the original fuel types obtained from the CFS. In addition, the Baseline (Model) scenario was generated from artificial data to be compatible with the climate change models.
   - **Time Period:** (1981 – 2010)

3. **CGCM (2050)**
   - **Model** : Canadian Center for Climate Modelling and Analysis (CGCM3.1)
   - **Time Period :** (2031 – 2060)

4. **CGCM (2080)**
   - **Model** : Canadian Center for Climate Modelling and Analysis (CGCM3.1)
   - **Time Period :** (2061 – 2090)

5. **HAD (2050)**
   - **Model** : Hadley Centre for Climate Prediction (HadCM3)
   - **Time Period** : (2031 – 2060)

6. **HAD (2080)**
   - **Model** : Hadley Centre for Climate Prediction (HadCM3)
   - **Time Period :** (2061 – 2090)

The purpose of this report is to describe the methods used and results of the Burn-P3 analysis that was developed and run in support of the project entitled 'Landscape Projections on Boreal Caribou Habitat in NWT - Summary Report' submitted to the Northwest Territory Government by Caslys Consulting Ltd.

Study Area

The study area for this project covers the southern portion of the boreal caribou range in the NWT, which overlaps the Dehcho and South Slave administrative regions. Figure 1 shows the location of the study area.

The study area encompasses an area of approximately 158 391 km^2. However, to allow for unrestricted burn modelling into and out of the study area, a 25 km buffer was added. The approximate size of the study area with the 25 km buffer is 212 916 km^2.

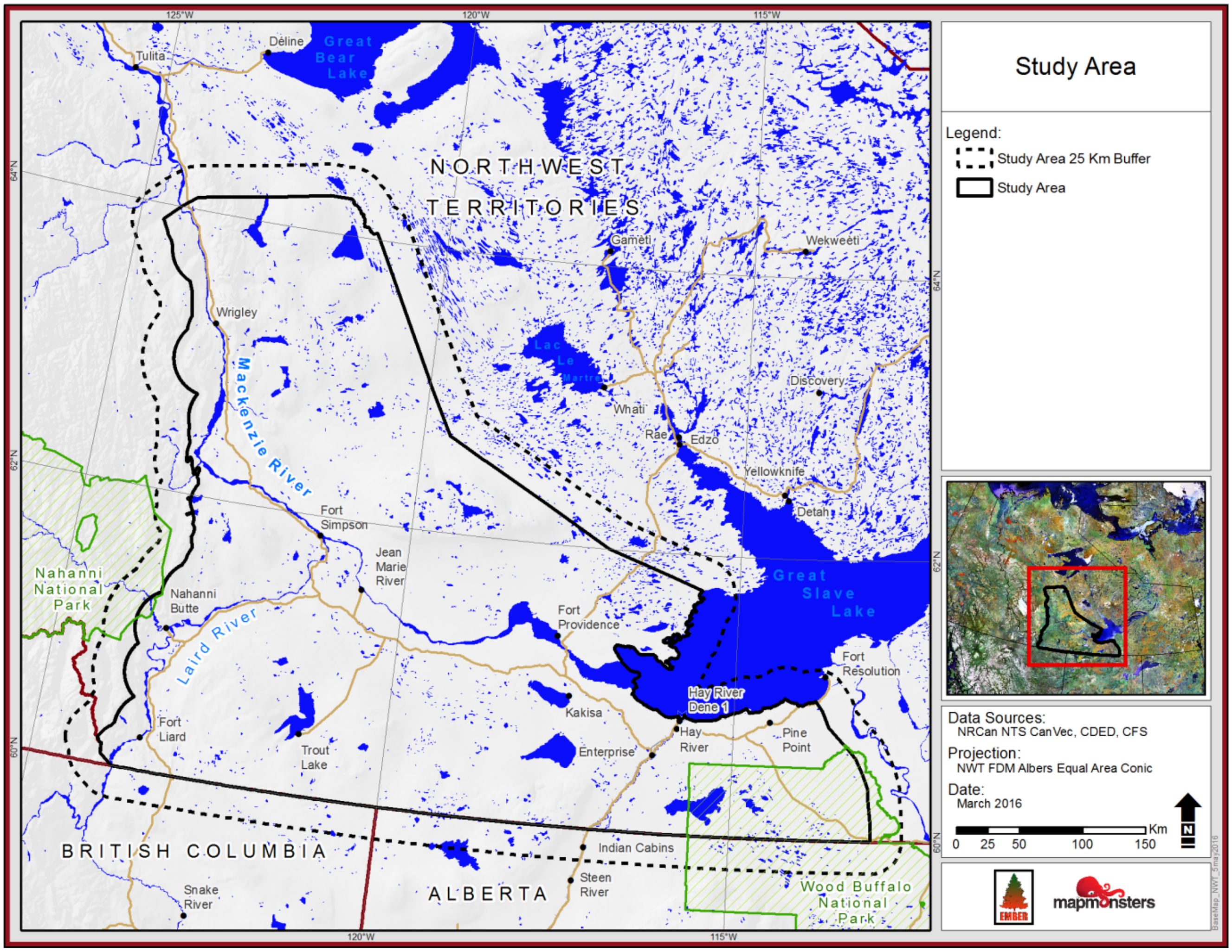

Figure 1. Study area.

METHODS

Burn-P3 Program

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

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

The two programs are described in Appendix 1 and the Burn-P3 program settings used for this NWT study area are described in detail within Appendix 2.

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.

Landscape Grids

The following landscape grids are required data input layers for the Burn-P3 program:

- Fire Behavior Prediction (FBP) System fuel type;
- elevation; and
- weather zones.

Optional landscape grids for the Burn-P3 program include:

- fire zones;
- ignition probability;
- wind speed; and
- wind direction.

For this analysis, we included fire zones (using the same boundaries as the weather zones) to allow for more control over the spread event day distributions by fire zone. Given the generally flat terrain within the study area, wind speed and wind direction grids were not required for this Burn-P3 analysis. All fire ignitions for this study are random lightning ignitions since there is insufficient fire history data to adequately model human-caused fires over such a large study area.

Given the large geographical area contained within this study area, the grid cell size selected for this analysis was 250m x 250m (6.25 ha).

All grid files used the Northwest Territories Albers Equal Area Conic projection. Table 1 describes the parameters for the landscape grid files.

Table 1. Landscape parameters of the study area grids.

			Location of Lower Left Corner	
Total area (Mha)	Cell Size (m)	Columns / Rows	Latitude	Longitude
21.29	250	2648 / 2251	59.178164º	-124.149599º

Fire Behavior Prediction (FBP) System Fuel Type Grids

The fuel grid, developed by the Canadian Forest Service, classifies land cover into the sixteen established fuel types of the Canadian FBP system, Forestry Canada Fire Danger Group (1992). The dataset used for this project was extracted from the National FBP System fuel database (version 4.3) maintained by Brian Simpson, Forest Analyst and Modeller with the CFS, Northern Forestry Centre, Edmonton, AB.

The difference between the Baseline (2015) fuels grid and the Climate Change Scenarios fuels grid is how recent fire history was classified. For the Baseline (2015) analysis, areas subject to fires within the last 5 years were classified as 'non-fuel' and areas subject to fires >5 and <= 10 years old were classified as a mixed-wood fuel with a 25% conifer component. The fuels grid used for the Climate Change Scenarios ignored recent fire history and used the original pre-burn fuel types. The pre-burn fuel types were used because fuel types following the recent fires would have been difficult to predict due to the confounded effects of climate change. Therefore, it would have been impossible to distinguish between natural changes in fuel versus changes in fuel type resulting from climate change. The purpose of running the Burn-P3 Climate Change scenarios is to determine the potential relative differences between the different climate change models and time periods, rather than to attempt to model the absolute differences in burn probability in response to potential changes in climate and potential changes in fuel types due to forest succession.

Figure 2 shows the map of the FBP System fuel types that were used for the Baseline (2015) Burn-P3 analysis and Figure 3 shows the FBP System fuel type map that was used for Climate Change Scenarios. Maps showing the areas affected by these fuel type changes are provided in Appendix 3.

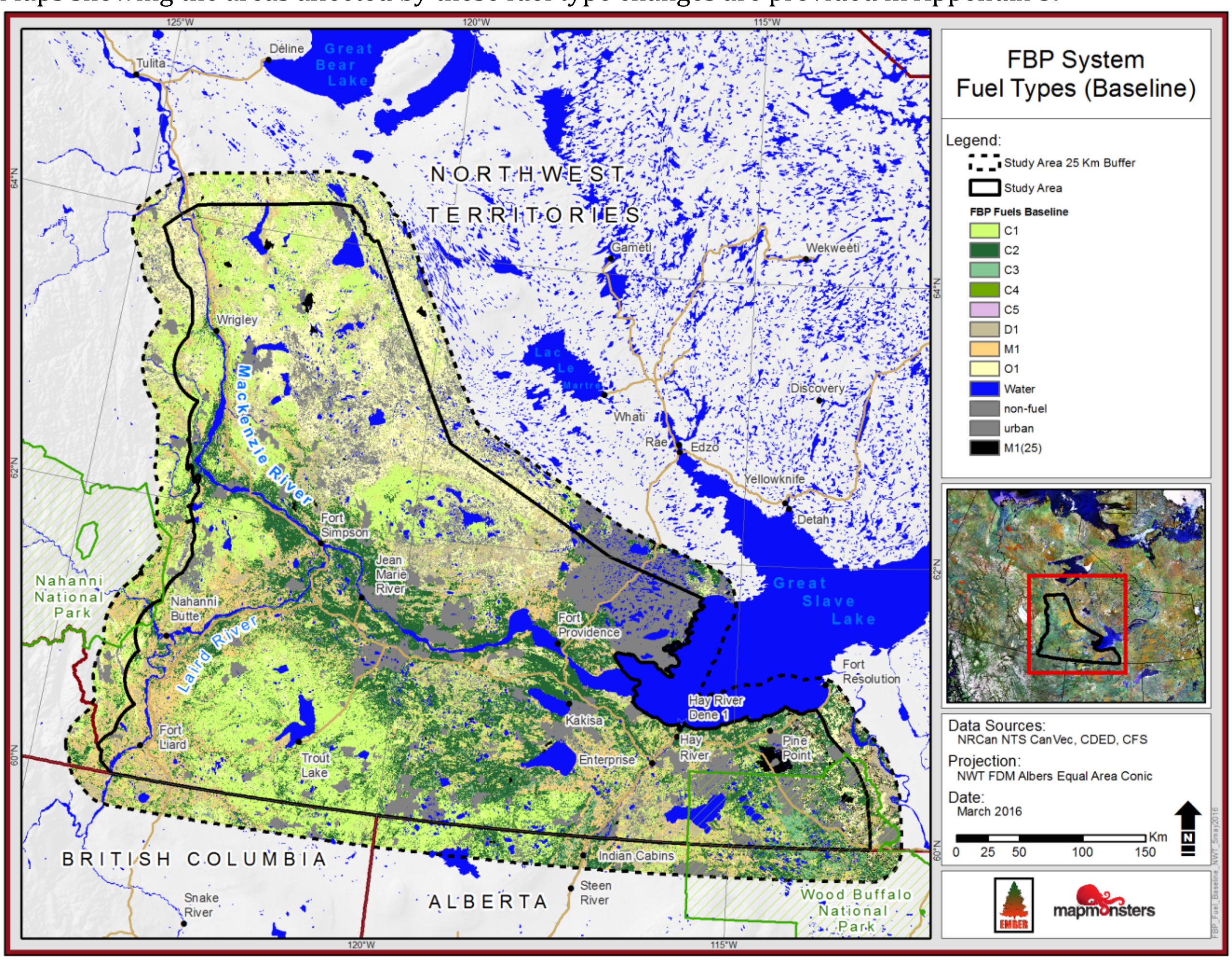

Figure 2. FBP System fuel type used for the Baseline (2015) analysis.

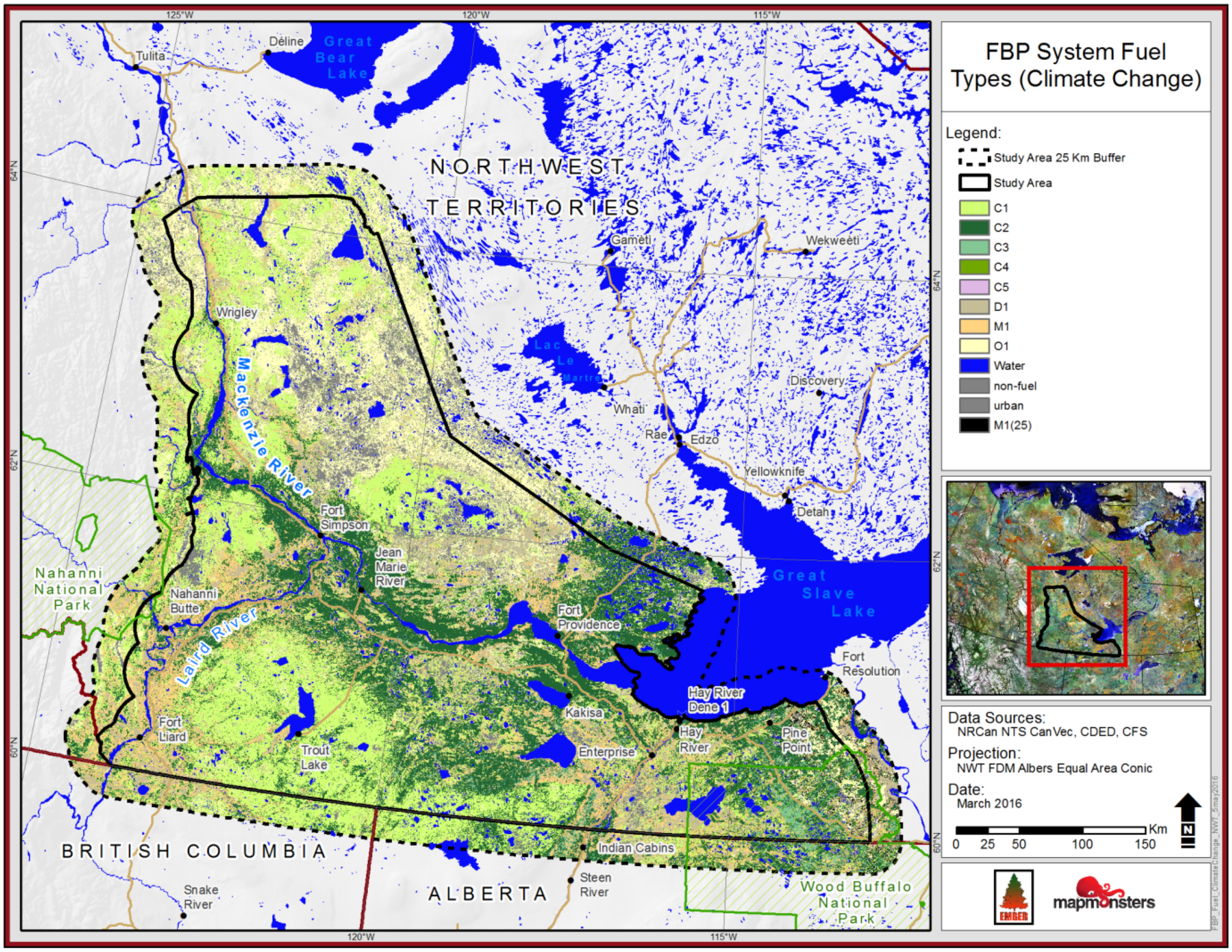

Figure 3. FBP System fuel type used for the Climate Change Scenarios.

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 4.

Table 2. Area and percentage of FBP System fuel types present in the study area.

FBP System fuel type code	FBP System fuel type name	Baseline (2015)		Climate Change Scenarios	
		Area (Mha)	Percentage of study area	Area (Mha)	Percentage of study area
C-1	C-1 Spruce-Lichen Woodland	4.9	23	5.4	25.3
C-2	C-2 Boreal Spruce	3.6	16.9	4.54	21.3
C-3	C-3 Mature Jack or Lodgepole Pine	0.4	2.0	0.52	2.5
C-4	C-4 Immature Jack or Lodgepole Pine	0.02	0.1	0.03	0.2
D-1/D-2	D-1/D-2 Aspen	1.7	7.9	1.79	8.4
M-1/M-2	M-1/M-2 Boreal Mixedwood	2.4	11.3	2.64	12.4
M-1 (25 PC)	M-1 Boreal Mixedwood – green (25% Conifer)	0.2	0.8	0.08	0.4
O-1a	O-1a Matted Grass	2.8	13.4	3.01	14.1
Non-fuel	Water	1.8	8.4	1.8	8.4
Non-fuel	Non-Fuel	3.4	16.2	1.48	7.0
	Totals	**21.29**	**100**	**21.29**	**100.0**

Elevation Grid

The elevation grid was created from Canadian Digital Elevation Data (CDED). The 25 metre raster pixels of the CDED was re-sampled to a 250 metre resolution to match the fuel input raster used in the Burn-P3 analysis.

Table 3 shows the elevation statistics for the study area and the map in Figure 4 displays the elevation range that occurs within the study area.

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

Minimum	25th Percentile	Median	Mean	75th Percentile	Maximum
71	221	291	349	449	1851

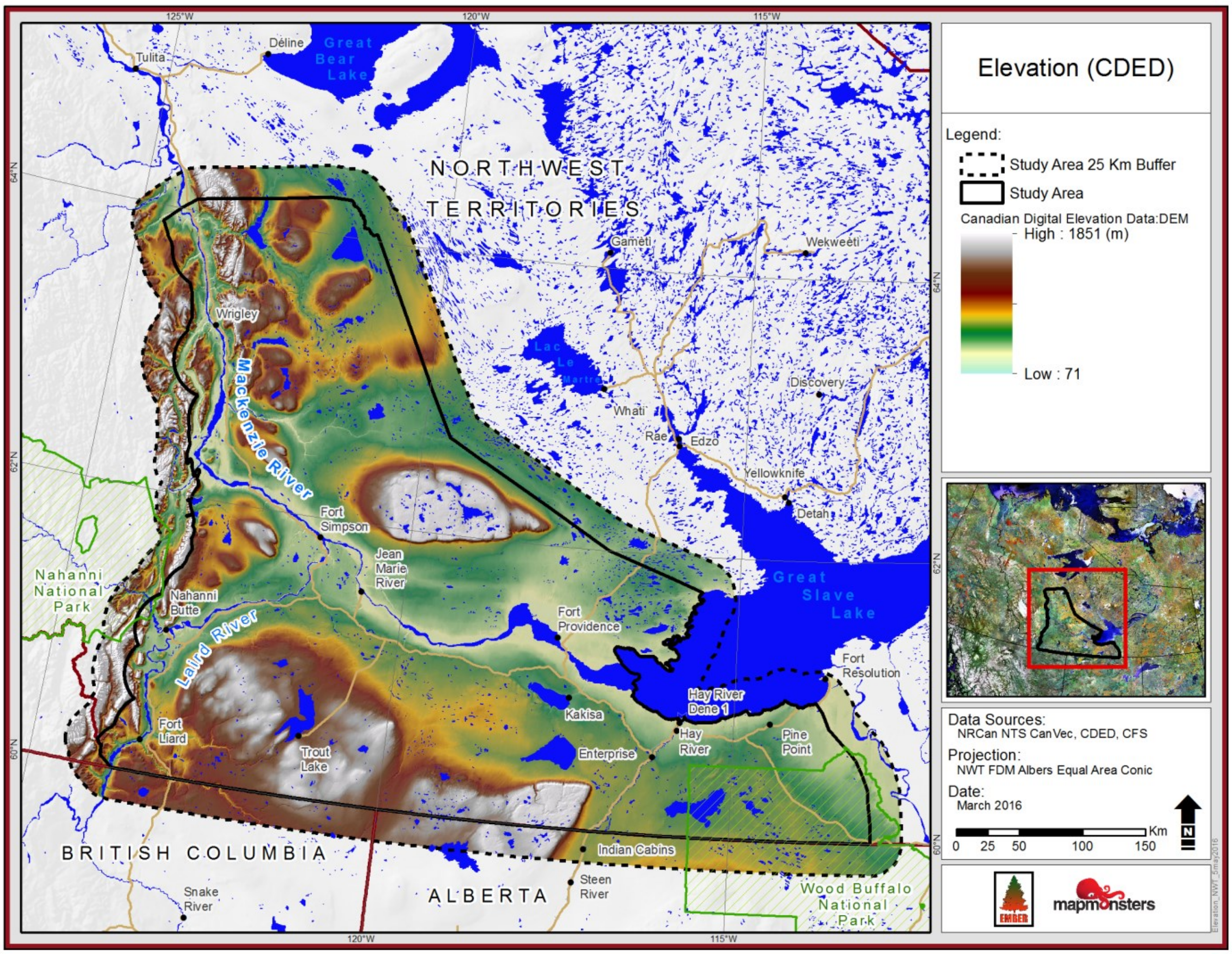

Figure 4. Elevation

Fire/Weather Zone Grid

Four weather zones were delineated for this study area as shown in Figure 5. These weather zones are based on the ecoprovince boundaries as described by Marshall et al. (1999). The only variation from the ecoprovince boundaries occurs along the western edge of the study area, as a thin wedge of an additional ecoprovince was incorporated into the westernmost weather zone to avoid creating a fifth small weather zone. Originally, the intent was to follow the method used for delineating weather zones as described in Armitage (2014), which resulted in 18 weather zones for this study area. However, as a result of discussions with CFS staff, it was determined that the resolution using the 18 zones was too fine for the climate change models and that the broader ecoprovinces were more appropriate (Evan Delancey and Marc Parisien, pers. Comm. February, 2016).

For the Burn-P3 analysis of this study area, fire zones were used to establish a geographical region where specific fire spread event day distributions would apply.

Table 4 shows the percentage of the study area within each Fire/Weather zone.

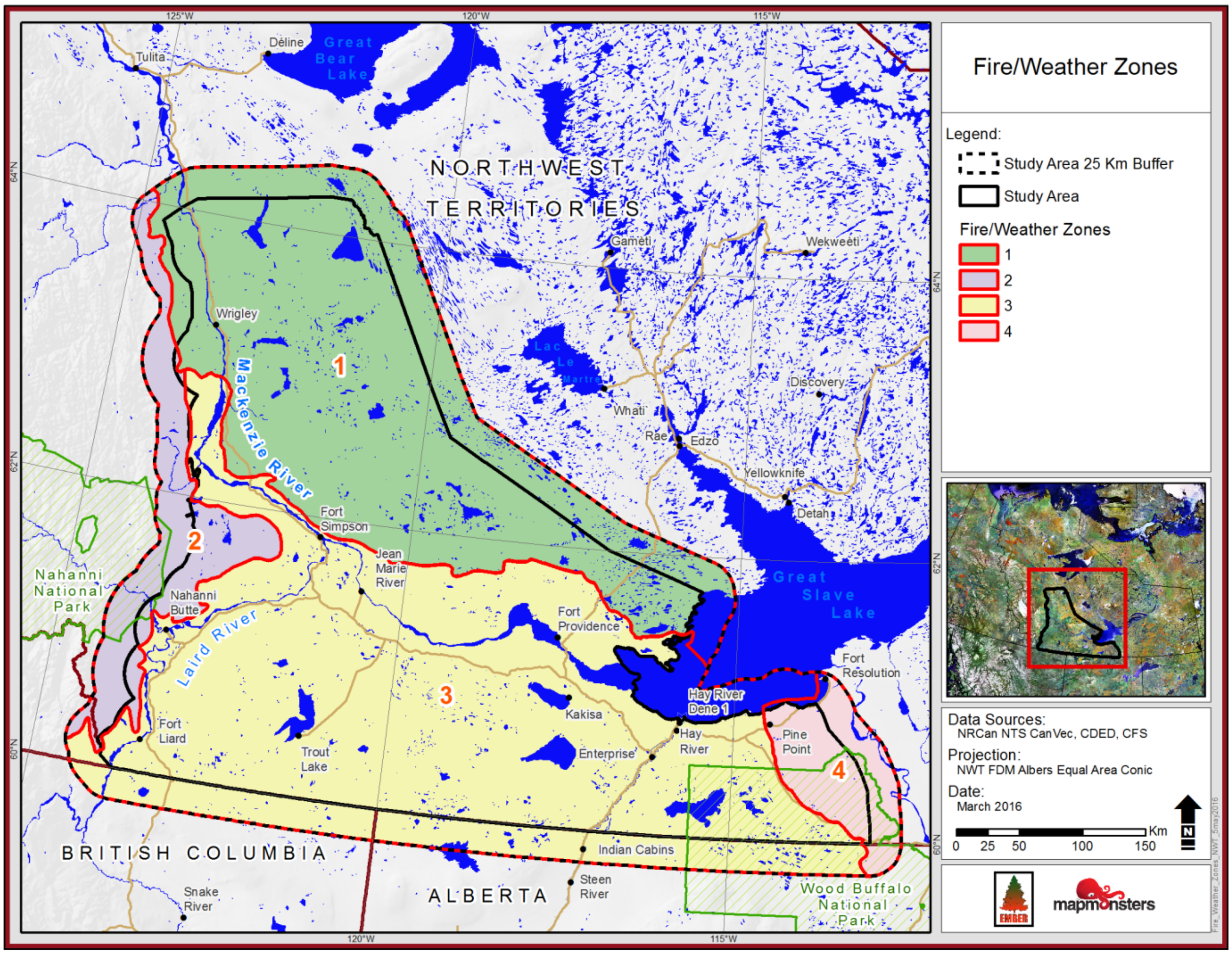

Figure 5. Fire/Weather zones

Table 4. Percentage of study area within each Fire/Weather zone.

Fire/Weather zone	1	2	3	4	Total
Area (Mha)	7.38	1.61	11.34	0.96	**21.29**
Percentage of study area	34.7	7.5	53.3	4.5	**100**

Fire History Data

The fire history within the current study area between the years 1950 and 2015 is displayed on the map in Figure 6.

The Burn-P3 analysis procedure utilizes data contained within the NWT fire history database in several ways, including:

- determining the distribution of escaped fires (ignitions) to simulate on the landscape for each iteration (year) of the simulation (See Figure A2.1);
- identifying areas of recent fire activity that require reclassification to non-fuel or mixed-wood on the FBP fuel type grid (See Figure A3.1);
- determining the escaped fire rates per fire zone (See Table A2.2);
- determining the historical fire size distribution present in the study area to assist with the calibration of the Burn-P3 model (See Figures 8 and 9).

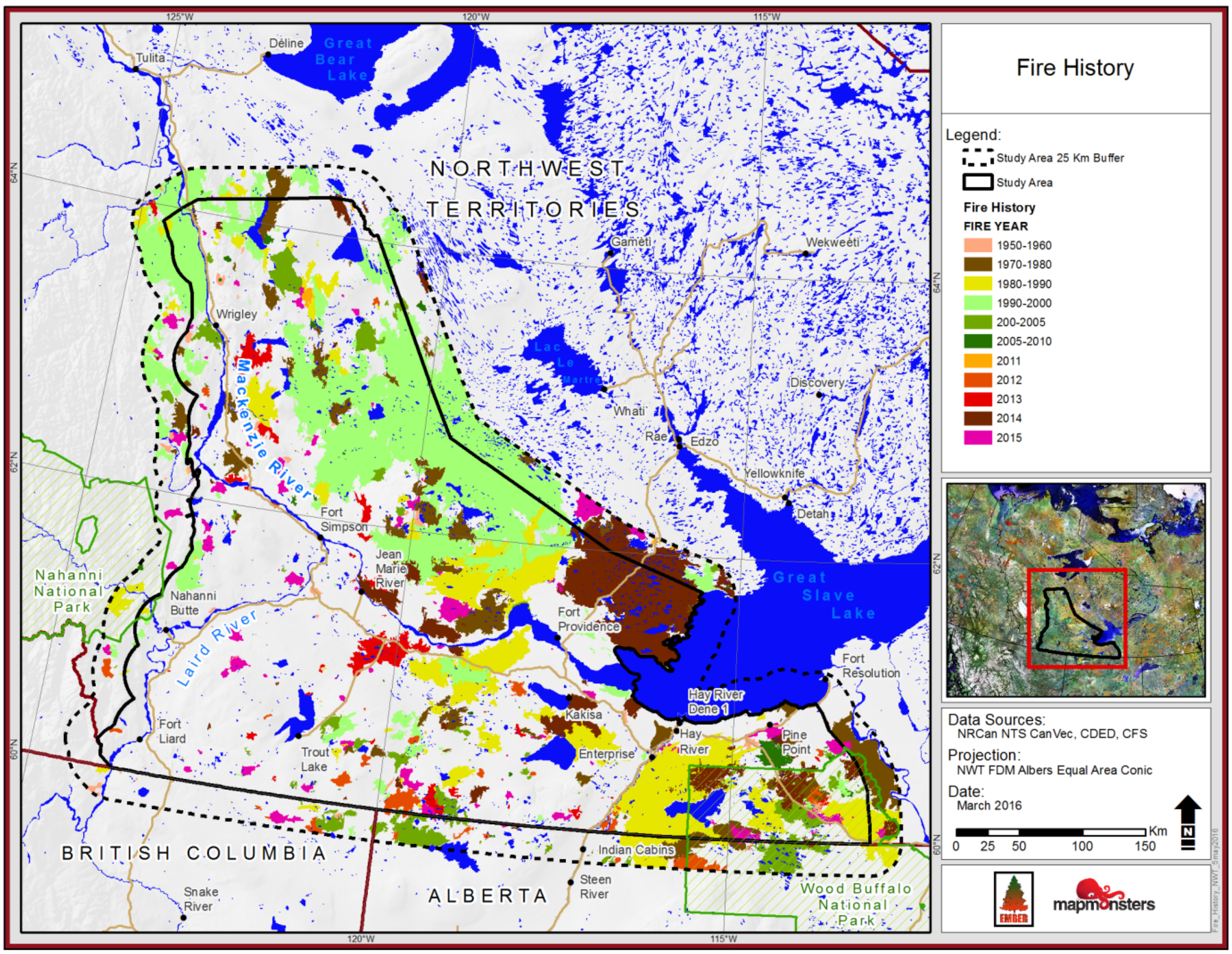

Figure 6. Fire history

Weather Data

The weather data used as inputs to the Burn-P3 analysis of this study area come from two different sources:

- the weather used in the Baseline (2015) scenario analysis originates from historical fire weather observations collected from weather stations within the study area; and
- weather records used in the Climate Change Scenarios are generated by extracting data from a climate change dataset created by University of Alberta and CFS researchers. The climate change weather data used in this Burn-P3 study is the same as is described in Wang et al. (2015).

Baseline (2015)

The fire weather data used for this NWT 2015 Burn-P3 analysis is the same that was used for the NWT 2014 Burn-P3 report (Armitage, 2014) consisting of daily fire weather records for select weather stations between 1954 and 2014, where the daily fire weather index (FWI) variable was greater or equal to 19. This FWI criteria of 19 is used to distinguish 'burning days' where a fire will spread (FWI >= 19) versus 'non-burning days' (FWI < 19). The use of the FWI criteria of 19 (to estimate burning vs non-burning days) is well established within the fire management and fire research communities within western Canada and is based on the research by Podur and Wotton (2011). The daily fire weather data records were assembled and pooled together by Fire/Weather zone. Appendix 5 contains a complete list of all of the weather stations within each weather zone that were used in this Burn-P3 analysis.

Climate Change Scenarios

The future fire weather data used in the Burn-P3 climate change scenario analysis was obtained courtesy of the University of Alberta's Western Partnership for Wildland Fire Science. The climate change data received from the CFS and University of Alberta researchers included artificial daily weather stream data and spread event day distributions for each climate change scenario. The daily weather stream data was generated for each Fire/Weather zone for each climate change scenario for each time period and included the following variables:

- weather zone;
- season;
- temperature;
- relative humidity;
- wind speed;
- wind direction;
- precipitation;
- Fine Fuel Moisture Content (FFMC);
- Duff Moisture Content (DMC);
- Drought Code (DC);
- Initial Spread Index (ISI);
- Buildup Index (BUI); and
- Fire Weather Index (FWI).

These data were produced with the delta approach (Flannigan et al., 2005), which uses monthly data from the Intergovernmental Panel on Climate Change (IPCC) Global Circulation Model (GCM) for future time periods and past time periods. The back-cast period is subtracted from a future time period for all climate variables, and a monthly anomaly is generated. This monthly anomaly is then added to observed daily fire weather for every point of interest. This method follows the same approach described by Wang et al. (2015). In the end, this approach resulted in future daily fire weather observations for 18 locations within four weather zones for four time periods: 2001-2030 (2020s), 2031-2060 (2050s), and 2061-2090 (2080s). The artificial daily weather stream data was then used directly as inputs into the Burn-P3 program for the climate change scenarios.

Spread event day distributions were also received from the CFS and University of Alberta researchers. Figure 7 shows the spread event day distributions that Burn-P3 used for each climate change scenario.

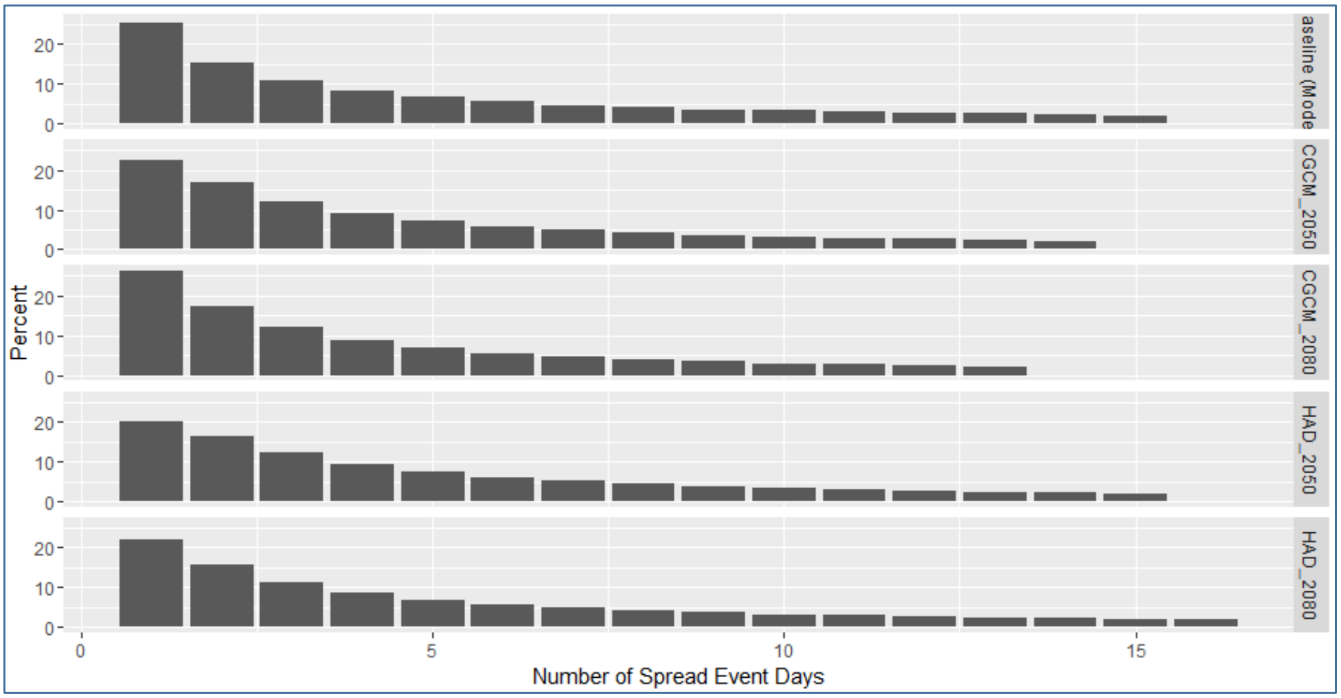

Figure 7. Spread event distributions for each climate change scenario.

Burn-P3 Model Set-up

Parameters

The Burn-P3 model parameters for this 2015 study area are the same or similar as those used in the previous 2014 study (Armitage 2014) with a few minor modifications to take into account the larger study area and modified weather zones etc. A complete description of the Burn-P3 model parameters is included in Appendix 2.

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.

Once all the Burn-P3 data inputs were assembled and loaded into a Burn-P3 project file (.bp3), a series of six 'calibration' runs were generated in order to calibrate the Burn-P3 model. The distribution of Burn-P3 generated fire sizes in a properly calibrated model should match the historical fire size distribution.

RESULTS

Calibration

The number of fires per year, area burned per year and fire size statistics are displayed in Table 5. In addition, Figure 8 shows how the fire size distribution compares between the Burn-P3 simulated fires and the historical database fires. Figure 9 shows the pre- and post-calibration cumulative proportion curves for log fire sizes by Fire/Weather zone.

As shown in Table 5, the number of fires per year are almost exactly the same for both the fire history database and the Burn-P3 simulated fires (14.8 and 14.2 respectively). In addition, for all fires > 30 and < 580 000 hectares, the median fire size is 747 and 738 hectares for the historical fire database and simulated Burn-P3 fires, respectively. Note that the decision was made to only include fires < 580 000 hectares for the calibration results since there were two fires in the historical fire database that were over 700 000 hectares and were considered outliers for this Burn-P3 calibration. Since it is very difficult to get Burn-P3 to model a few very rare large fires without altering the fire size distribution of the smaller fires, these two large fires (> 700 000 ha) were excluded from the statistics shown in Table 5.

The boxplots in Figure 8 show differences between the logarithm (log) of the fire sizes (ha) of the historical fires and the Burn-P3 simulated fires (following the calibration process) for the entire study area as well as by Fire/Weather zone. Note that there are slight differences in some of the 25th and 75th percentiles (bottom of box and top of box respectively); however, the median values (black horizontal line in the middle of the box) are very close.

Figure 9 displays the pre- and post-calibration cumulative proportion curves for the log(fire sizes) (hectares) by Fire/Weather zone and it is apparent from these results that the cumulative proportion lines for the fire history and Burn-P3 log fire sizes are much closer following the calibration process.

Table 5. Calibration Statistics for fires >= 30 ha and < 580 000 ha in size

	Fire History Database	Burn-P3 Calibration
Number of Fires per Year	14.8	14.2
Area Burned (ha) per year	125 524	103 476
Median Fire Size (ha)	747	738
Mean Fire Size (ha)	8 368	7 295
Maximum Fire Size (ha)	526 223	578 319

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

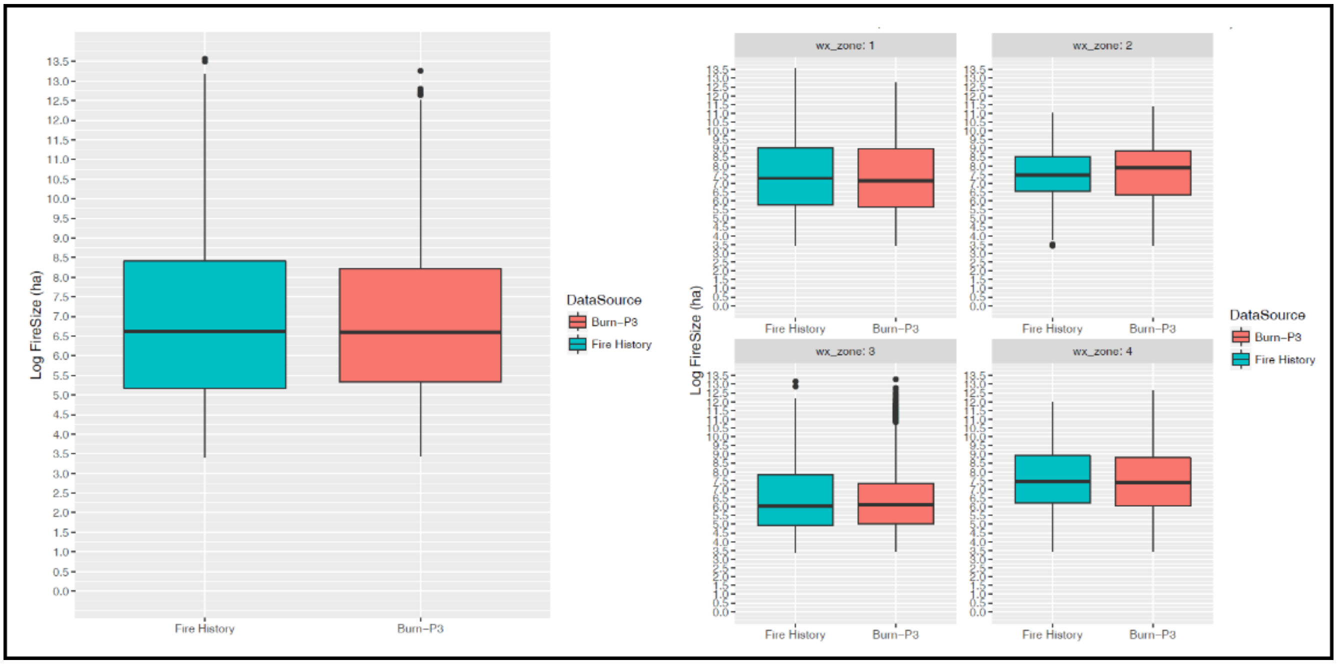

Figure 8. Post-calibration comparisons of Log fire sizes (fire history database vs. Burn-P3 simulated fires).

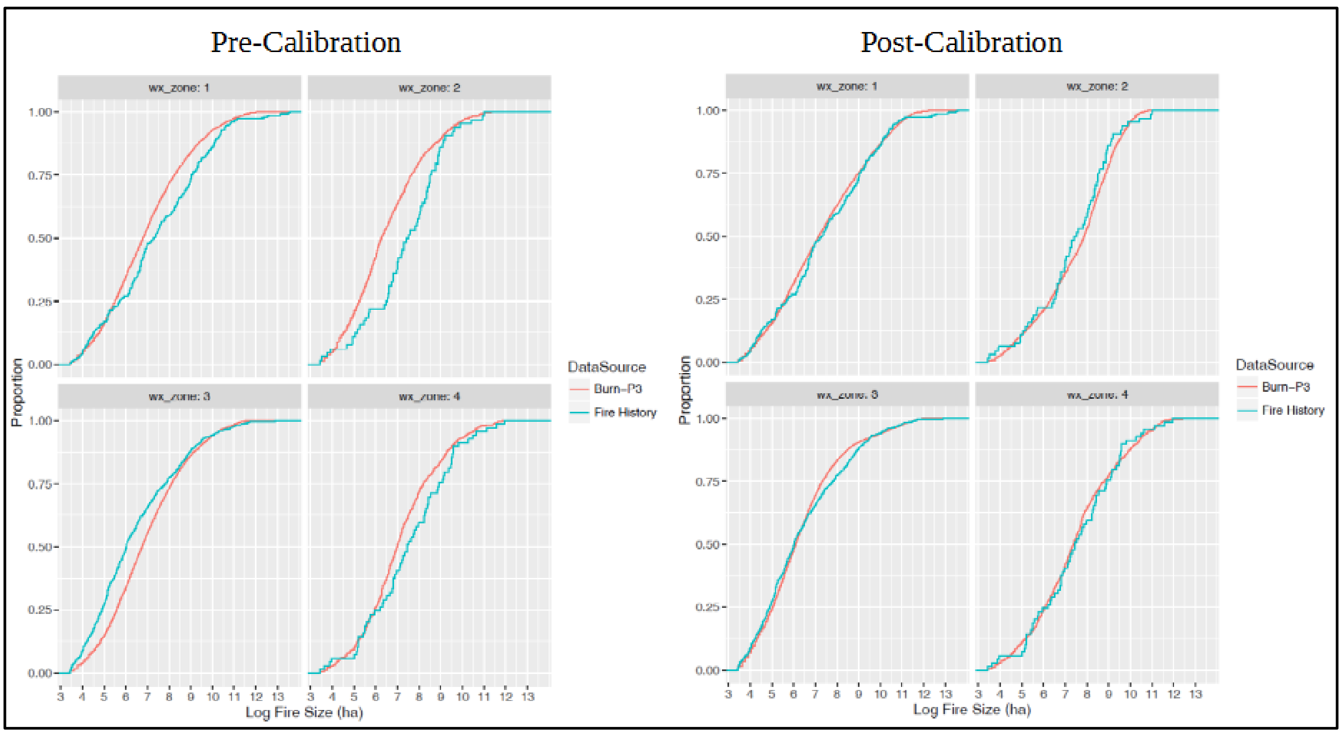

Figure 9. Pre- and post-calibration results on the cumulative proportion curves of Log Fire Size (ha) (by Fire/Weather zone).

Iterations

The Burn-P3 program simulates a large number of fires on the study area landscape. Table 6 shows the number of iterations and number of fires that were completed for each of the Burn-P3 scenarios completed for this study area and the resulting density of ignitions (that resulting in fires > 30 hectares in size) per 1000 hectares of burnable fuel.

Table 6. Number of iterations and fires simulated for each Burn-P3 scenario.

Scenario	Number of Iterations	Number of Fires	Area (M ha)	Number of Simulated Fires / 1000 ha of burnable fuel
Baseline (2015)	70 254	1 008 984	21.29	62.9
Baseline (Model)	40 043	574 118	21.29	35.8
CGCM 2050	40 022	575 500	21.29	35.9
CGCM 2080	39 842	571 929	21.29	35.6
HAD 2050	40 852	590 011	21.29	36.8
HAD 2080	39 638	567 044	21.29	35.3

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 (e.g., ≥ 30 ha).

Baseline (2015)

Table 7 shows the burn probability and fire size statistics for the calibrated Burn-P3 Baseline (2015) scenario results and the map in Figure 10 shows the spatial distribution of burn probability (%) values within the study area.

Table 7. Burn probability (%) and fire size statistics for the Baseline (2015) scenario results.

Baseline (2015)	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.19	0.59	0.44	0.76	2.78	3.76
Fire size statistics	31	212	8110	806	4 419	113 240	433 056

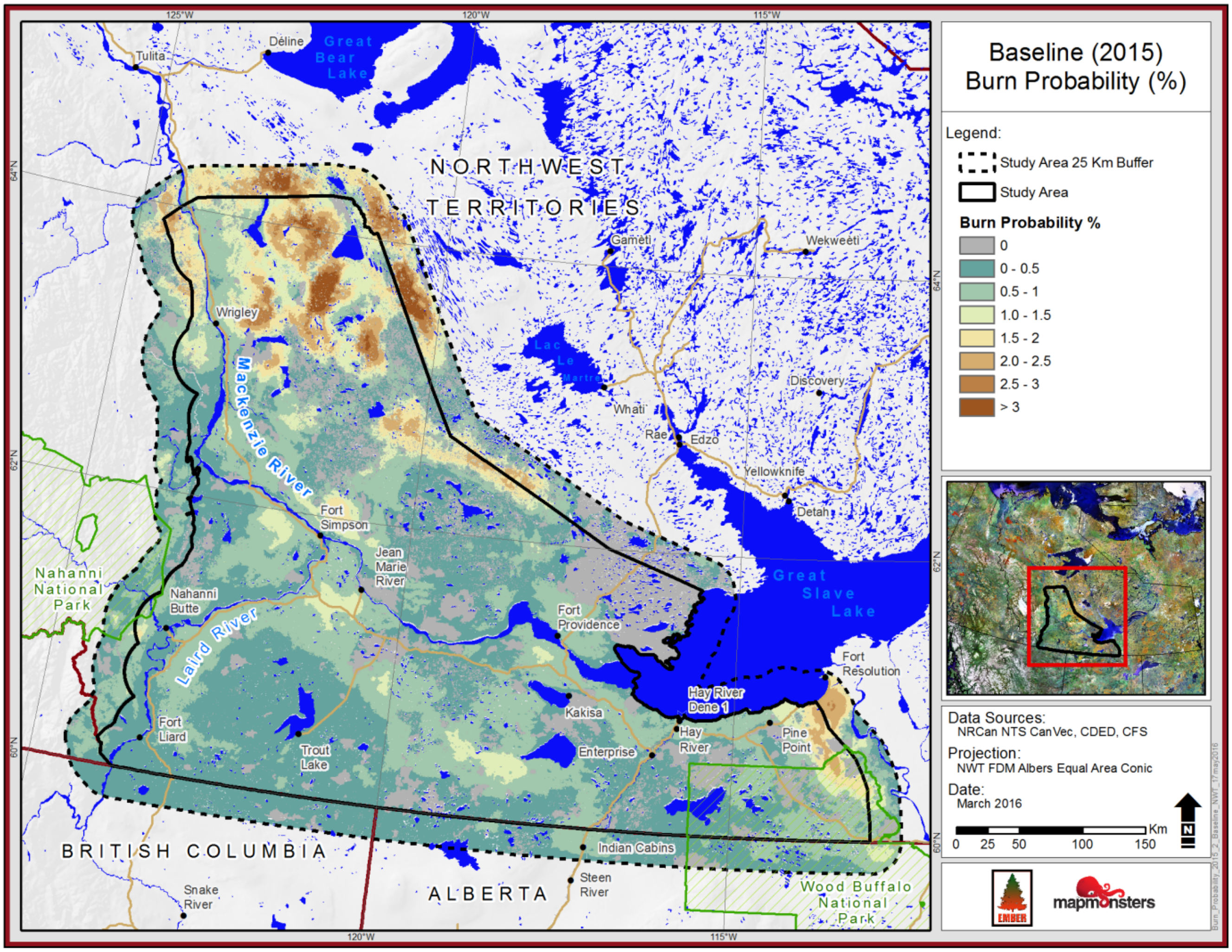

Figure 10. Burn probability (%) Baseline (2015).

Climate Change Scenarios

Baseline (Model)

Table 8 shows the burn probability and fire size statistics for the Burn-P3 Baseline (Model) scenario results and the map in Figure 11 shows the spatial distribution of burn probability (%) values within the study area.

Table 8. Burn probability (%) and fire size statistics for the Baseline (Model) scenario results.

Baseline (Model)	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.28	0.85	0.67	1.31	3.00	3.69
Fire size statistics	31	431	11 799	2 362	11 919	107 808	377 594

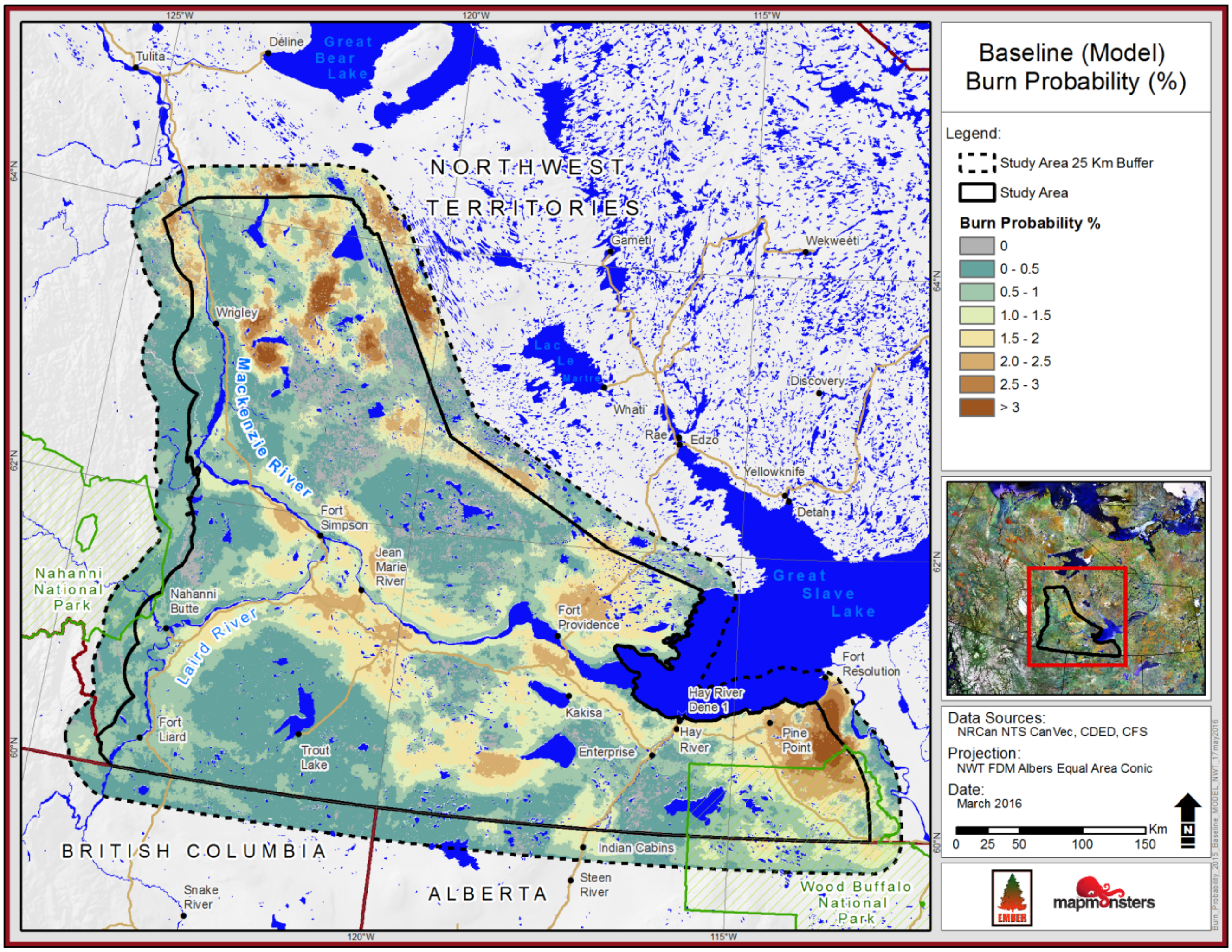

Figure 11. Burn probability (%) Baseline (Model).

CGCM 2050

Table 9 shows the burn probability and fire size statistics for the Burn-P3 CGCM 2050 scenario results and the map in Figure 12 shows the spatial distribution of burn probability (%) values within the study area.

Table 9. Burn probability (%) and fire size statistics for the CGCM 2050 scenario results.

CGCM 2050	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.40	0.81	0.69	1.17	2.56	3.68
Fire size statistics	31	475	11 161	2 512	11 512	101 950	341 775

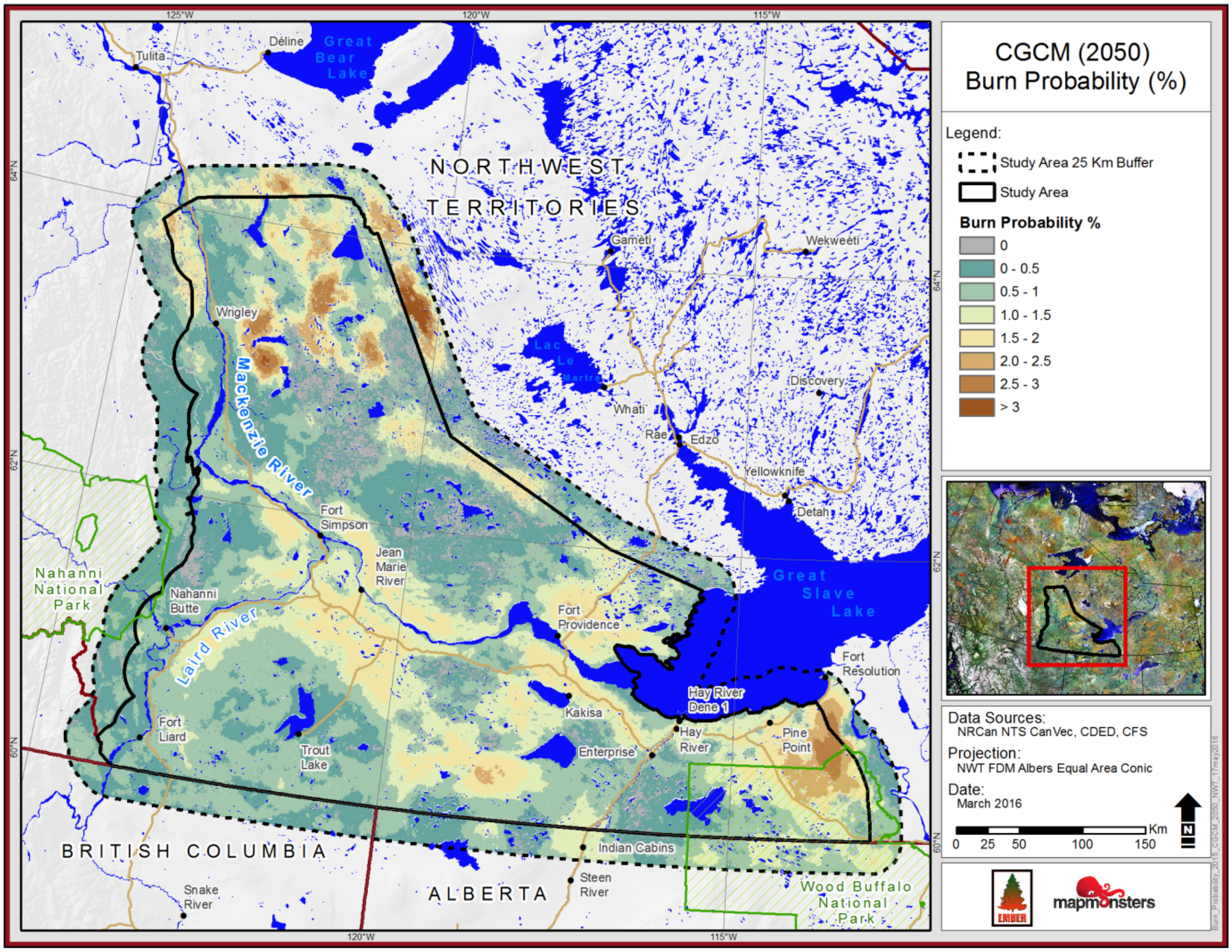

Figure 12. Burn probability (%) CGCM 2050.

CGCM 2080

Table 10 shows the burn probability and fire size statistics for the Burn-P3 CGCM 2080 scenario results and the map in Figure 13 shows the spatial distribution of burn probability (%) values within the study area.

Table 10. Burn probability (%) and fire size statistics for the CGCM 2080 scenario results.

CGCM 2080	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.37	0.76	0.65	1.10	2.42	3.36
Fire size statistics	31	444	10 528	10 507	10 706	97 602	361 388

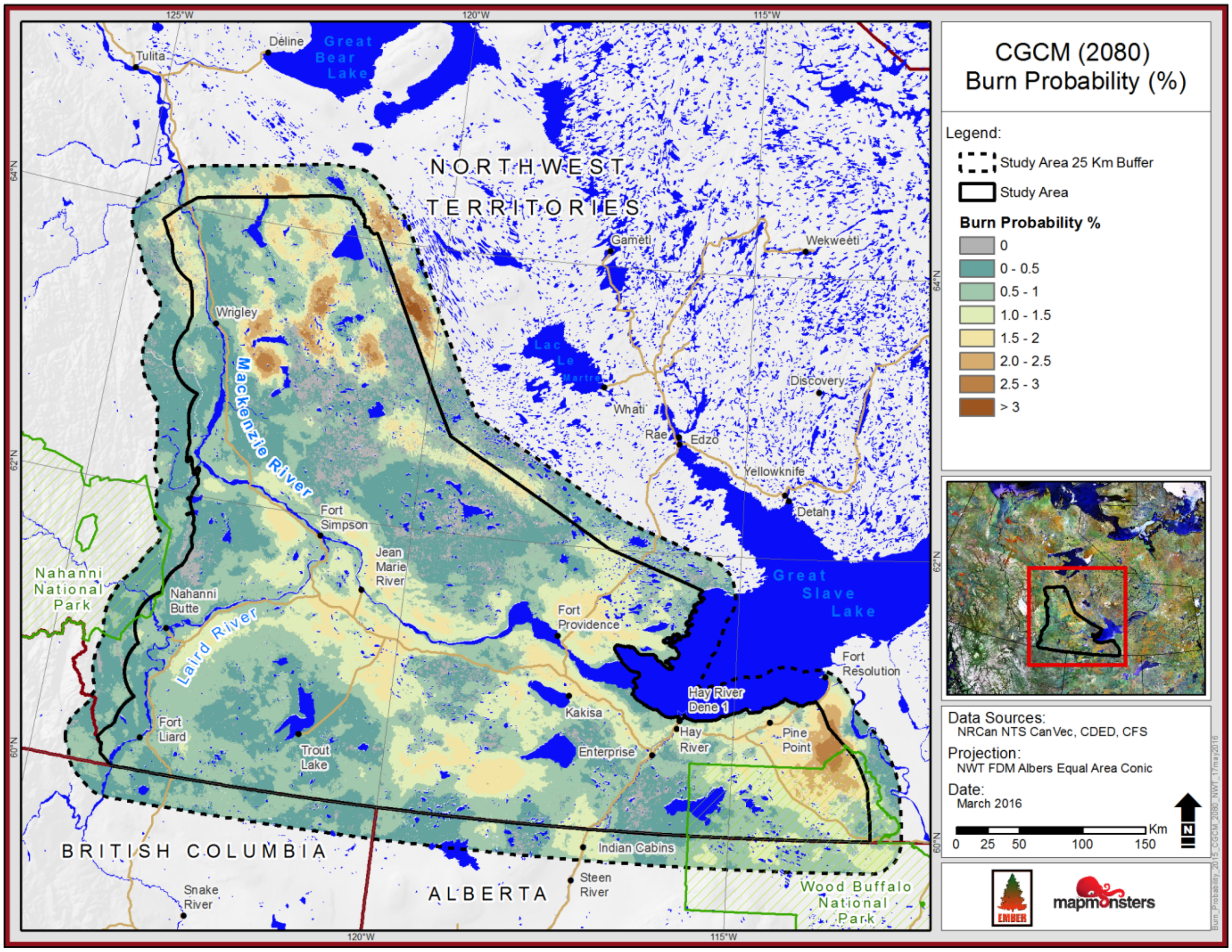

Figure 13. Burn probability (%) CGCM 2080.

HAD 2050

Table 11 shows the burn probability and fire size statistics for the Burn-P3 HAD 2050 scenario results and the map in Figure 14 shows the spatial distribution of burn probability (%) values within the study area.

Table 11. Burn probability (%) and fire size statistics for the HAD 2050 scenario results.

HAD 2050	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.52	1.03	0.89	1.47	3.21	4.38
Fire size statistics	31	606	14 145	3 288	14 918	150 512	411 869

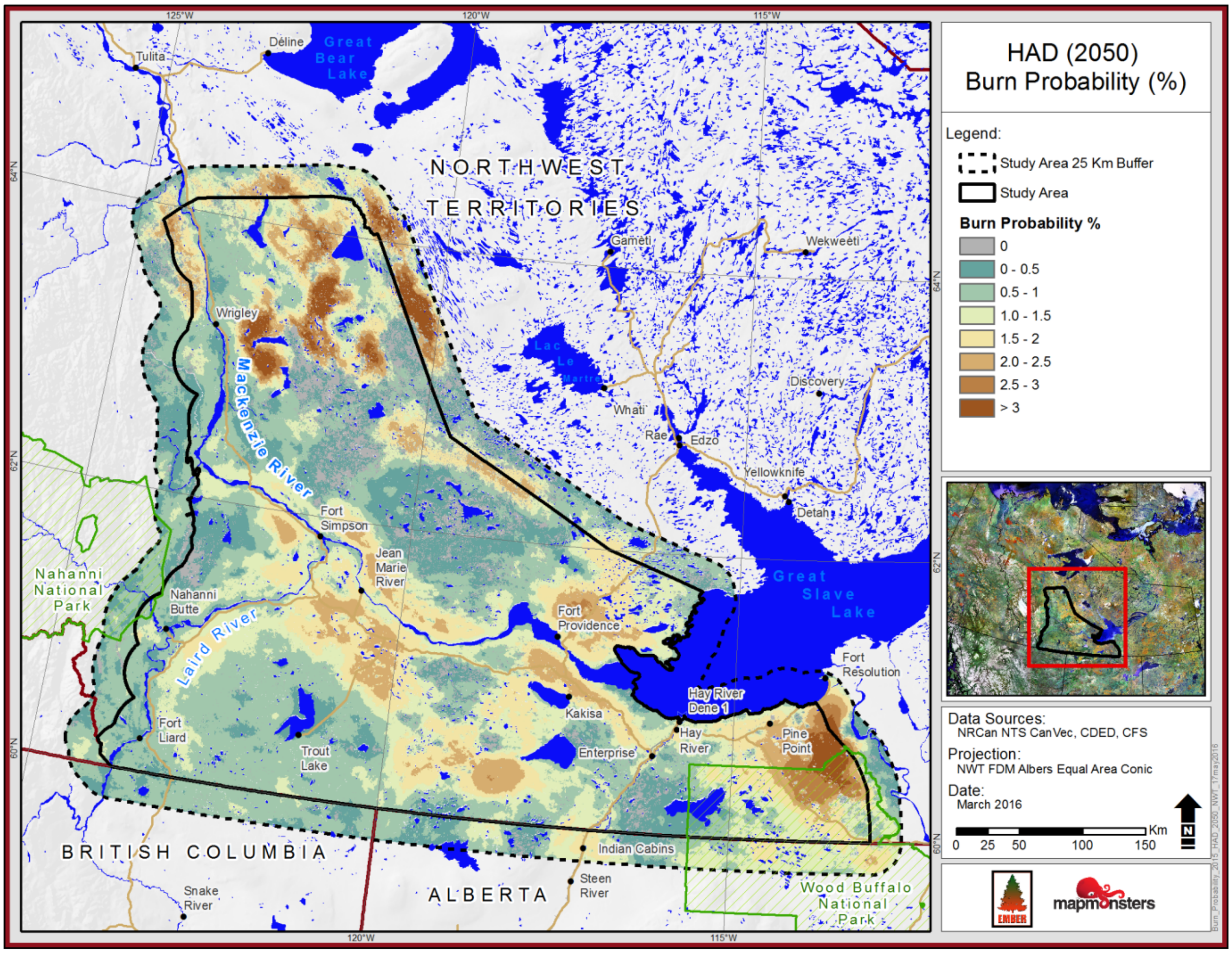

Figure 14 Burn probability (%) HAD 2050.

HAD 2080

Table 12 shows the burn probability and fire size statistics for the Burn-P3 HAD 2080 scenario results and the map in Figure 15 shows the spatial distribution of burn probability (%) values within the study area.

Table 12. Burn probability (%) and fire size statistics for the HAD 2080 scenario results

HAD 2080	Minimum	25th Percentile	Mean	Median	75th Percentile	99th Percentile	Maximum
Burn probability (%)	0.00	0.52	1.05	0.91	1.53	3.14	4.07
Fire size statistics	31	556	14 682	3 169	15 381	131 012	555 838

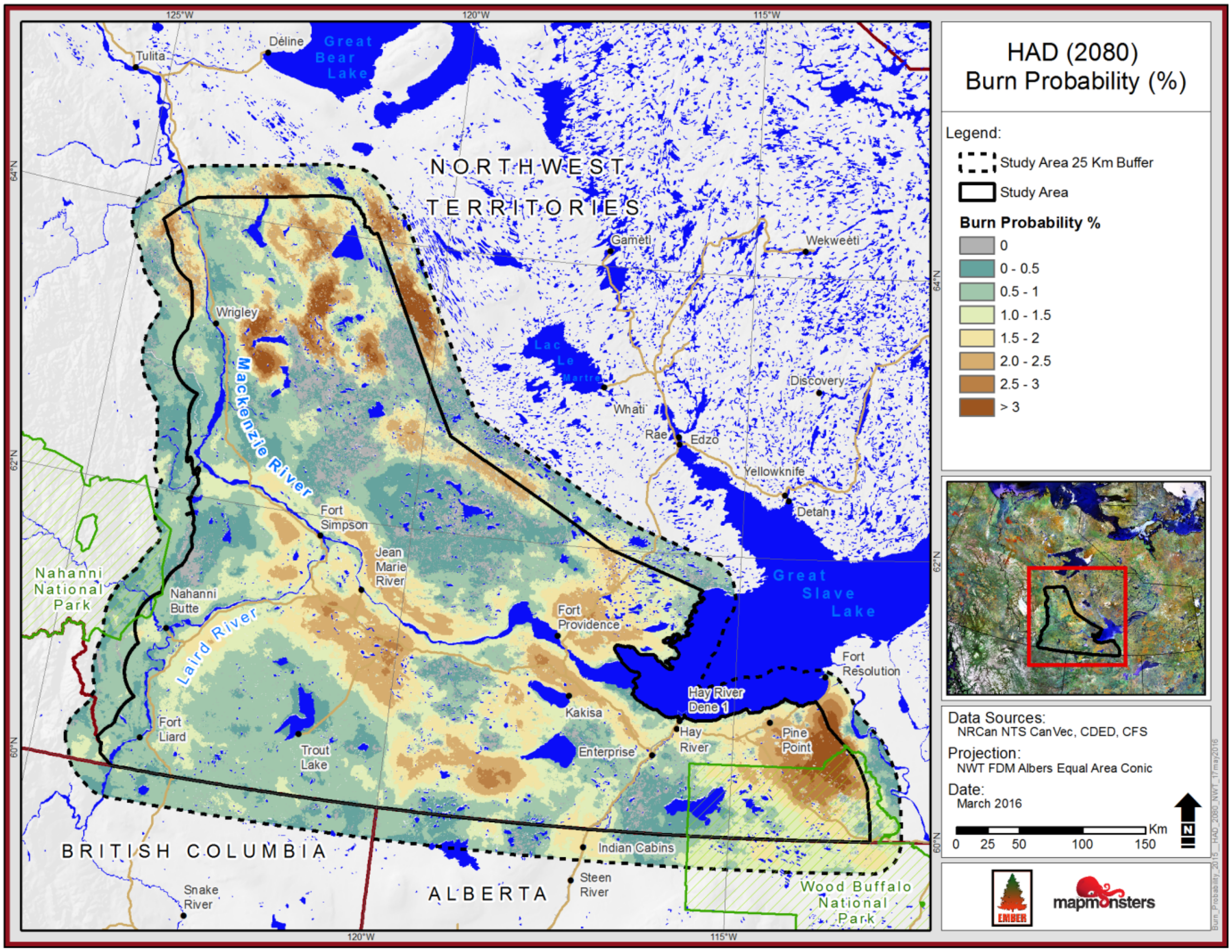

Figure 15. Burn probability (%) HAD 2080.

DISCUSSION

Baseline (2015) Results

Calibration

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 study area (including the 25 km buffer) is over 212 900 km^2 (> 21.29 million hectares) and is considered large for a Burn-P3 analysis. In addition, several of the Fire/Weather zones have very different fire history characteristics. For example, Fire/Weather zones 1 and 3 (see Figure 5) have very different levels of fire activity recorded within the fire history database (see Figure 6), which is reflective of the combination of fuel types, topography, fire weather conditions and potential ignition sources. The fire size distributions within each of the four Fire/Weather zones may respond differently to changes in the various Burn-P3 model parameters, and so, the challenge is to find the optimal solution that minimizes the differences in fire size distribution across all Fire/Weather zones.

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 very good.

The results of the calibration process for this study area are consistent with other Burn-P3 studies recently completed in the NWT and Yukon territories.

Burn Probability

The Baseline (2015) burn probability ranges from a minimum of 0% to a maximum of 3.76% as summarized in Table 13. Although the maximum burn probability recorded in the study area was 3.76%, the 99^{th} percentile value of the burn probability was 2.78%. These results indicate that only 1 % of the grid cells in the study area had a burn probability greater than 2.78%.

Table 13. Summary of Baseline (2015) burn probability statistics

		Burn Probability (%)			
Scenario	**Time Period**	**Minimum**	**Average**	**99^{th} Percentile**	**Maximum**
Baseline (2015)	**2015**	**0.00**	**0.59**	**2.78**	**3.76**

The Baseline (2015) burn probability map shown in Figure 10 shows distinct 'hot spots' of higher burn probability. A visual analysis of the burn probability map indicates that most of these hot spots are well correlated with the areas classified as grass (O-1) fuel type. This grass fuel type is assumed to be the closest representative and most appropriate FBP System fuel type to use given that the fuels information originated from the CFS and is constantly updated as new technology and remote sensing information becomes available. However, none of the fuel types have been ground-truthed to verify the accuracy of the fuel type classification from remote sensing data.

Climate Change Scenario Results

Predicted Future Burn Probability

The average burn probability over the entire study area landscape for all climate change scenarios ranges between 0.76% and 1.05 % for the CGCM 2080 and HAD 2080 scenarios respectively as shown in Table 14. The 99^{th} percentile burn probability ranged from 2.42% to 3.21% for the CGCM 2080 and HAD 2050 scenarios respectively.

Table 14. Summary of climate change scenario burn probability statistics

		Burn Probability (%)			
Scenario	**Time Period**	**Minimum**	**Average**	**99th Percentile**	**Maximum**
Baseline (Model)	1981 - 2010	0.00	0.85	3.00	3.69
CGCM	2050	0.00	0.81	2.56	3.68
CGCM	2080	0.00	0.76	2.42	3.31
HAD	2050	0.00	1.03	3.21	4.39
HAD	2080	0.00	1.05	3.14	4.07

Note that some of the results shown in Table 14 appear counter-intuitive. For example, the average burn probability of the CGCM 2050 time period (0.81%) is reduced to (0.76%) for the 2080 time period. Negative trends associated with the CGCM model were also observed by Wang et al. (2015) and were attributed to projected increases in precipitation. Given the random inputs of future daily weather and future spread event day distributions into the Burn-P3analysis, it is not unexpected that some of the Burn-P3 burn probabilities could also display negative trends.

Predicted Future Fire Size

The distribution of fire size from all of the simulated fires in each of the Burn-P3 scenarios is shown in Figure 16. Like the burn probability results, there are a few counter-intuitive results such as the 2050 scenarios having a lower median fire size than the 2080 scenarios for both the CGCM and HAD climate change models. This decrease in median fire size for the CGCM climate model can be explained by the same rationale as the observed decrease in the 95th percentile FWI described by Wang et al. (2015). A change in forecasted precipitation patterns and the resulting change on the artificially generated weather streams would result in changes to the Burn-P3 modeled fire sizes.

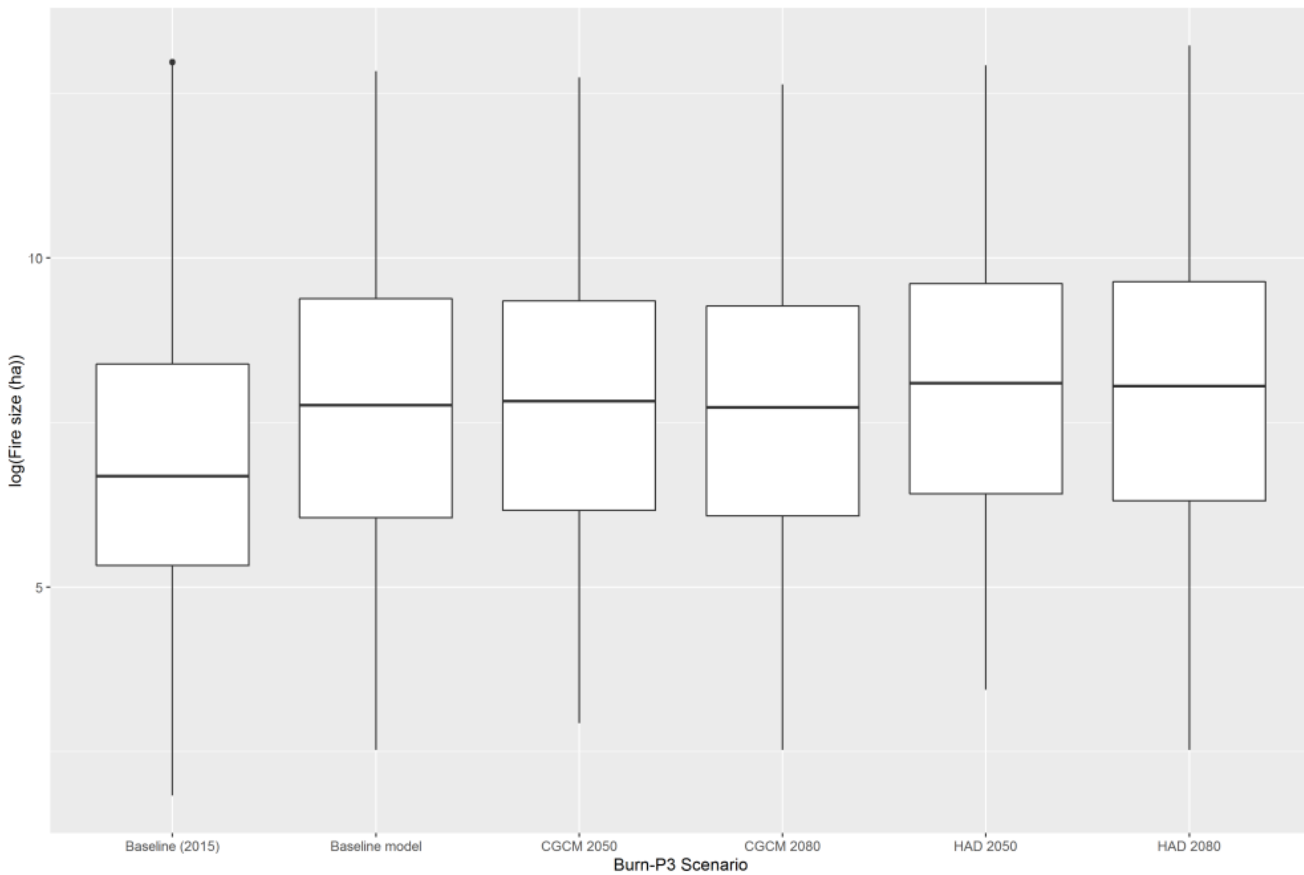

Figure 16. Fire size distribution log(ha) of Burn-P3 simulated fires by scenario

The observed decrease in the median fire size going from the HAD 2050 model results to the HAD 2080 model results is also a bit counter-intuitive. However, if the mean, the 75th percentile and maximum fire sizes are compared, the fire size differences between the HAD 2050 and HAD 2080 climate change models increase as expected. The mean, 75th and maximum fire sizes for the HAD 2050 and HAD 2080 Burn-P3 fire sizes are shown in Tables 11 and 12, respectively.

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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

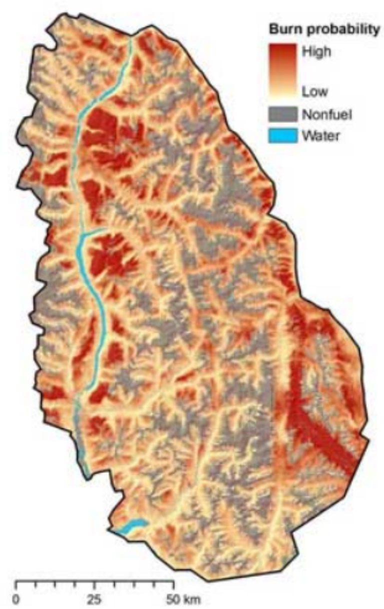
The software was developed by Marc-André Parisien from the Canadian Forest Service (CFS), with the collaboration of Parks Canada, the Canadian Interagency Forest Fire Centre (CIFFC), the Canadian Boreal Forest Agreement (CBFA), the Province of Alberta, the Province of British Columbia, and the Province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

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.

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.

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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.

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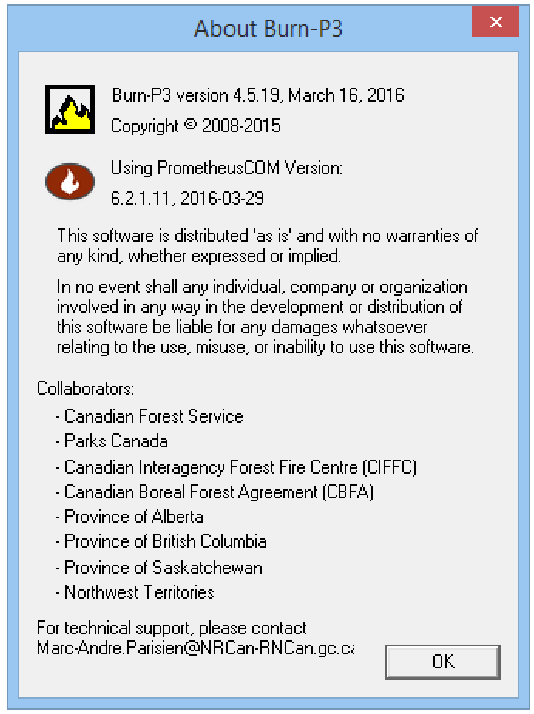
The Prometheus fire growth model

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

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

Burn-P3 settings
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	
	Number of escaped fires	Distribution	See Figure A2.1
	Escaped fire rates	Distribution	See Table A2.2
Burning conditions module	Fire weather list	YT historical weather ISI >=8	See Table A5.1 in Appendix 5
	Daily fire weather selection method	Random	
	Number of spread-event days (by weather zone)	Distribution	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	

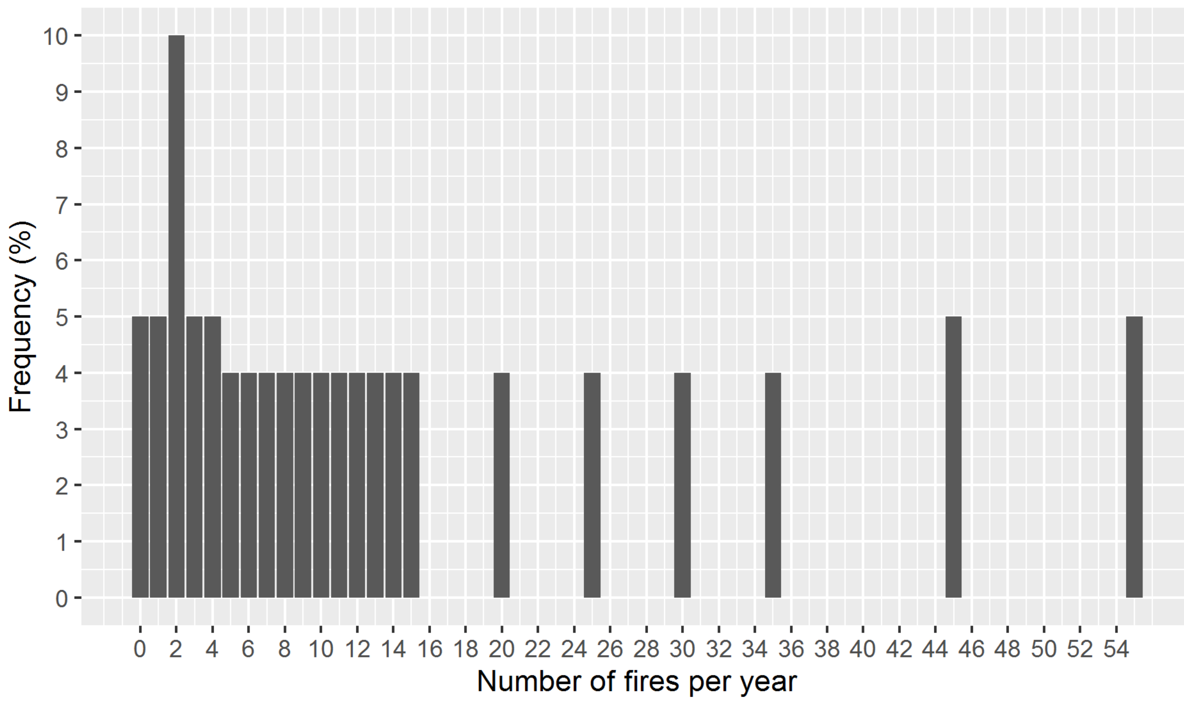


Figure A2.1. Distribution of escaped fires – Percentage of escaped fires per iteration (year).

Table A2.2. Distribution of escaped fire rates.

Season*	Cause*	Weather zone	Escaped fire rate
1	1	1	13.25
2	1	1	13.25
1	1	2	3.4
2	1	2	3.4
1	1	3	29.7
2	1	3	29.7
1	1	4	3.65
2	1	4	3.65
		Total	**100**

*Season 1 = 'Spring' ; 2 = 'Summer' / Cause 1 = 'Lightning'

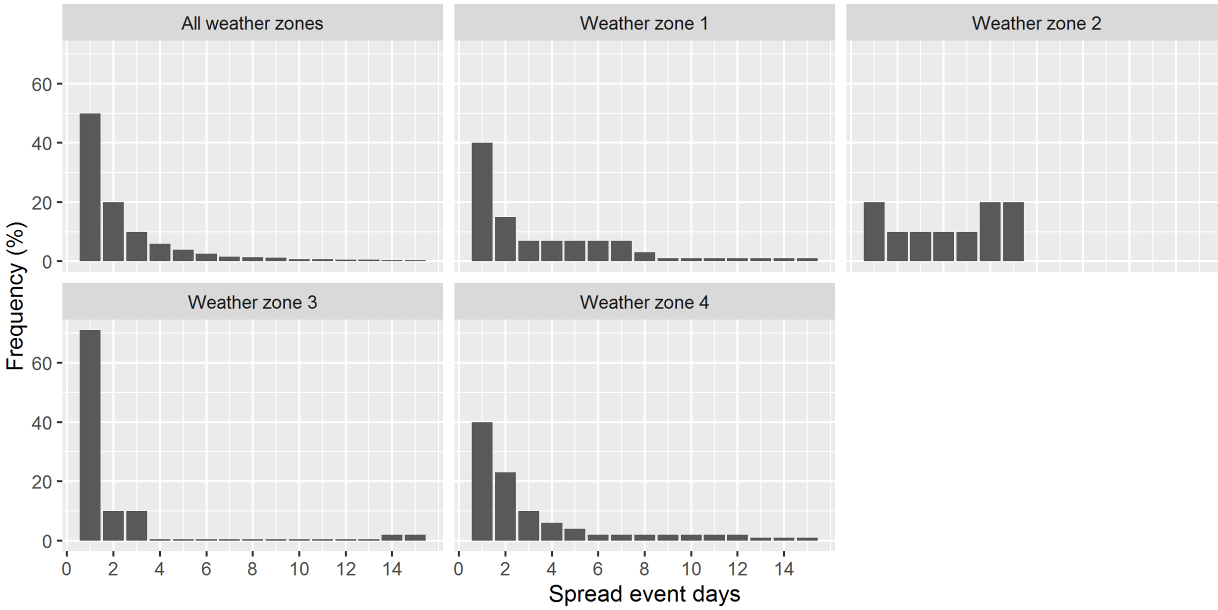


Figure A2.2. Distribution of spread-event days by weather zone.

Table A2.3. Distribution of burning hours per day.

Burning hours per day	1	2	3	4	5	6	7	8	9	10
Percent	0	0	20	20	20	10	10	20	0	0

Appendix 3: Fuel Type Grid Modifications

Conversion of areas of recent fire activity (≤ 10 years old).

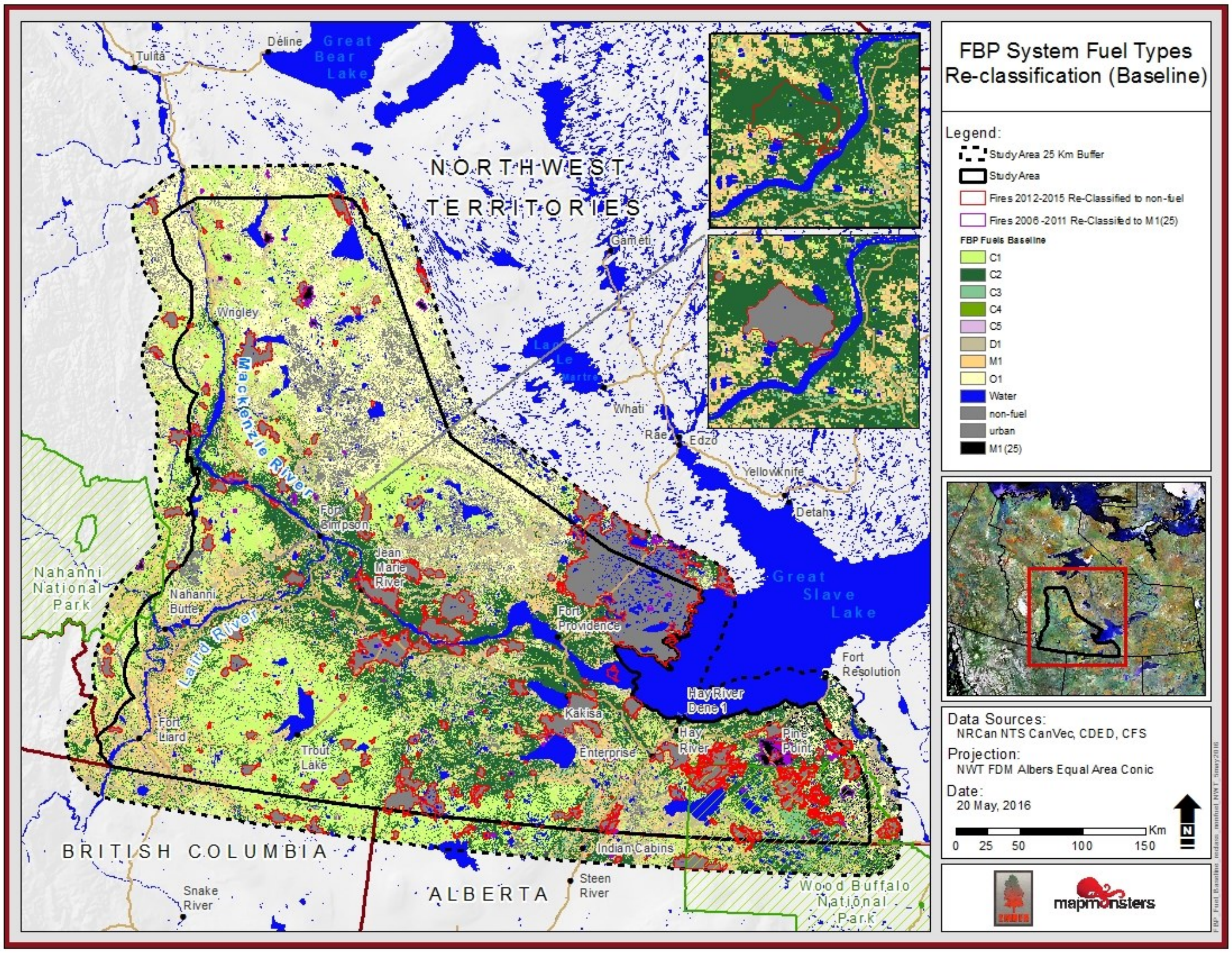


Figure A3.1. Map indicating the areas of recent fire activity (≤ 5 years) re-classified to non-fuel and fire activity >5 years and ≤ 10 years re-classified to M1 (25% conifer).

Appendix 4: 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 (chiefly*Cladonia*). *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.).

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.

	**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 papyrifera*Marsh.). 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/c1

Appendix 5: Weather zones and weather stations used in the Burn-P3 analysis.

Table A5.1. List of weather zones and weather stations used in the Burn-P3 analysis.

Weather Zone	Period of Record*	Weather Stations used	Latitude	Longitude	Elevation (m)
Weather zone 1	1964 – 2013	Horn Tower	61.93331	-119.8192	734
		Cean Lake Tower	61.67958	-116.9714	231
		Crown Fire	61.5828	-117.165	193
		Fort Simpson	61.86943	-121.3643	123
		Jean Marie – Mobile 2	61.3172	-120.676	222
		Mosquito Creek Tower	62.54947	-116.4842	298
Weather zone 2	1981 – 2013	Lone Mountain Tower	62.1887	-123.3348	672
		Mount Gaudet	63.34333	-123.6	572
		Wrigley	63.20752	-123.429	271
		FS-002 Mobile 5	63.0876	-123.229	202
		CWJL	60.235	-123.4669	237
		CYJF	60.2355	-123.47	230
		Fort Liard	60.23586	-123.4728	225
		JFTR	60.2833	-123.45	271
		LINDBERG LANDING AUT	61.125	-122.8511	180
		Nahanni Butte	61.0854	-123.3818	1386
		YJF	60.2355	-123.47	230
Weather zone 3	1954 – 2013	Fort Providence	61.35	-117.667	168
		Samba Deh Park – Mobile 2	61.1434	-119.845	203
		JP	61.31764	-117.604	157
		Kimble Tower	61.05	-117.55	216
		HayRiver	60.78619	-115.8224	170
		Angus Tower	60.43682	-114.3083	270
		Sandy Lake	60.53042	-114.592	259
		Trout Lake Tower	60.43333	-121.45	700
		FS002-2004	60.09366	-121.2086	683
		Lone Mountain	60.433	-121.45	700
		Cameron Hills Tower	60.30105	-117.0623	865
		Grumbler Creek	60.2417	-116.576	285
		Border AB	60.00063	-116.981	291
		Mile 99	60.14687	-113.64	270
Weather zone 4	1954 – 2013	Fort Resolution	61.1649	-113.6567	166
		Little Buffalo Tower	60.99719	-113.7817	191
		YFR	61.1808	-113.6897	159
		Long Island Tower	60.721	-112.9986	190
		Fort Smith HQ	60.0026	-111.909	207

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

Appendix C
EOSD Fuel Translation Matrices

Translating Land Cover to Fuel

An overlay of EOSD land cover classes and fuel codes in unburned areas (tables C-1 and C-2) provided the basis for the translation matrices that allowed fuel codes to be determined from EOSD land cover classes in recently burned areas. The translation matrices, one for higher elevation terrain (Table C-3) and one for lower elevation terrain (Table C-4), incorporate subjective judgement. The matrices were used to translate non-fuel and open fuel types in recently burned areas (post 1950) to a 'recovered' fuel type based on the land cover class and a randomly generated cumulative probability score.

Table C-1. Proportion of Area of each Fuel Code in each EOSD Land Cover Class in High-elevation Terrain (>500 m)

EOSD Class	Land Cover	Fuel Codes (high elevation terrain)						
		C1	C2	Decid	M1	Open	Non Fuel	Water
0	No Data	0.41	0.16	0.05	0.06	0.08	0.06	0.17
1	Shadow	0.42	0.02	0.03	0.02	0.30	0.21	0.01
2	Water	0.16	0.04	0.00	0.02	0.03	0.02	0.74
3	Rock/Rubble	0.33	0.03	0.02	0.04	0.30	0.27	0.01
4	Exposed Land	0.31	0.01	0.01	0.01	0.34	0.30	0.02
5	Bryoids	0.64	0.01	0.02	0.01	0.21	0.09	0.02
6	Shrub_Tall	0.27	0.02	0.10	0.19	0.32	0.09	0.00
7	Shrub_Low	0.48	0.03	0.09	0.09	0.21	0.09	0.01
8	Wetland_Treed	0.74	0.09	0.02	0.03	0.06	0.06	0.01
9	Wetland_Shrub	0.72	0.07	0.03	0.05	0.07	0.04	0.01
10	Wetland_Herb	0.57	0.06	0.02	0.04	0.19	0.10	0.02
11	Herbs	0.43	0.01	0.07	0.08	0.18	0.21	0.01
12	Conif_Dense	0.58	0.31	0.02	0.06	0.02	0.00	0.01
13	Conif_Open	0.71	0.13	0.03	0.05	0.06	0.01	0.01
14	Conif_Sparse	0.77	0.06	0.03	0.02	0.09	0.02	0.01
15	Broadleaf_Dense	0.16	0.07	0.35	0.39	0.03	0.00	0.00
16	Broadleaf_Open	0.14	0.10	0.29	0.44	0.02	0.00	0.00
17	Mixedwood_Dense	0.29	0.20	0.14	0.33	0.03	0.01	0.01
18	Mixedwood_Open	0.56	0.24	0.03	0.08	0.07	0.02	0.01

Table C-2. Proportion of Area of each Fuel Code in each EOSD Land Cover Class in Low-elevation Terrain (<500 m)

EOSD Class	Land Cover	Fuel Codes (low elevation terrain)							
		C1	C2	Decid	M1	NA	Open	Non F	Water
0	No Data	0.11	0.32	0.06	0.14	0.32	0.03	0.01	0.02
1	Shadow	0.41	0.06	0.02	0.08	0.00	0.08	0.14	0.21
2	Water	0.03	0.03	0.01	0.03	0.00	0.02	0.01	0.87
3	Rock/Rubble	0.49	0.16	0.05	0.10	0.01	0.06	0.07	0.06
4	Exposed Land	0.14	0.26	0.05	0.12	0.00	0.10	0.16	0.18
5	Bryoids	0.28	0.02	0.17	0.08	0.00	0.37	0.07	0.02
6	Shrub_Tall	0.10	0.27	0.25	0.28	0.00	0.05	0.02	0.04
7	Shrub_Low	0.22	0.10	0.14	0.10	0.00	0.35	0.06	0.02
8	Wetland_Treed	0.24	0.33	0.09	0.16	0.00	0.13	0.03	0.01
9	Wetland_Shrub	0.27	0.31	0.11	0.19	0.00	0.07	0.04	0.02
10	Wetland_Herb	0.22	0.17	0.12	0.16	0.00	0.23	0.07	0.03
11	Herbs	0.28	0.07	0.17	0.13	0.00	0.25	0.07	0.02
12	Conif_Dense	0.19	0.60	0.02	0.15	0.00	0.02	0.00	0.01
13	Conif_Open	0.28	0.39	0.06	0.16	0.00	0.10	0.01	0.01
14	Conif_Sparse	0.33	0.25	0.10	0.13	0.00	0.15	0.03	0.01
15	Broadleaf_Dense	0.04	0.18	0.32	0.43	0.00	0.01	0.00	0.02
16	Broadleaf_Open	0.03	0.30	0.20	0.43	0.00	0.00	0.01	0.02
17	Mixedwood_Dense	0.06	0.31	0.15	0.45	0.00	0.01	0.00	0.01
18	Mixedwood_Open	0.25	0.26	0.10	0.22	0.00	0.12	0.02	0.01
19	Mixedwood_Sparse	0.00	0.47	0.04	0.39	0.00	0.04	0.04	0.00

Table C-3. Estimated Cumulative Probability of Fuel Codes in each EOSD Land Cover Class for High Elevation Terrain (> 500m)*

Land Cover	Estimated Cumulative Probability (%) for Elevations > 500 m									
	10	20	30	40	50	60	70	80	90	100
0:No_Data	1	1	1	1	1	8	9	19	19	19
1:Shadow	1	1	1	1	1	8	9	19	19	19
2:Water	1	1	1	1	1	1	1	1	1	1
3:Rock_Rubble	1	1	1	4	16	16	16	19	19	19
4:Exposed Land	1	1	1	1	1	1	1	1	1	1
5:Bryoids	1	1	1	1	1	1	1	16	16	19
6:Shrub_Tall	1	1	1	1	8	9	9	16	16	16
7:Shrub_Low	1	1	1	1	1	1	9	16	16	19
8:Wetland_Treed	1	1	1	1	1	1	1	1	9	9
9:Wetland_Shrub	1	1	1	1	1	1	1	1	9	9
10:Wetland_Herb	1	1	1	1	1	1	1	16	16	19
11:Herbs	1	1	1	1	1	9	16	16	19	19
12:Conif_Dense	1	1	1	1	1	1	1	1	1	1
13:Conif_Open	1	1	1	1	1	1	1	1	1	9
14:Conif_Sparse	1	1	1	1	1	1	1	1	1	16
15:Broadleaf_Dense	1	1	8	8	8	8	9	9	9	9
16:Broadleaf_Open	1	1	8	8	8	8	9	9	9	9
17:Mixedwood_Dense	1	1	1	1	1	1	8	9	9	9
18:Mixedwood_Open	1	1	1	1	1	1	1	1	8	9
19:Mixedwood_Sparse	1	1	1	1	1	1	1	1	8	9

Each cell in the table shows the fuel code assigned for the probability class.

Table C-4. Modified Cumulative Probability of Fuel Codes in each EOSD Land Cover Class for Lower Elevation Terrain (< 500m)*

Land Cover	Estimated Cumulative Probability (%) for Elevations < 500 m									
	10	20	30	40	50	60	70	80	90	100
0:No_Data	2	2	2	2	2	8	9	19	19	19
1:Shadow	2	2	2	2	2	8	9	19	19	19
2:Water	2	2	2	2	2	2	2	2	2	2
3:Rock_Rubble	2	2	2	2	9	16	16	19	19	19
4:Exposed Land	2	2	2	2	2	2	2	2	2	2
5:Bryoids	2	2	2	8	8	9	16	16	16	16
6:Shrub_Tall	2	2	2	2	2	8	9	9	8	16
7:Shrub_Low	2	2	2	2	8	8	9	16	16	16
8:Wetland_Treed	2	2	2	2	2	2	2	8	9	9
9:Wetland_Shrub	2	2	2	2	2	2	2	8	9	9
10:Wetland_Herb	2	2	2	2	2	8	9	16	16	19
11:Herbs	2	2	2	2	8	8	9	9	16	16
12:Conif_Dense	2	2	2	2	2	2	2	2	2	9
13:Conif_Open	2	2	2	2	2	2	8	9	9	16
14:Conif_Sparse	2	2	2	2	2	2	8	9	9	16
15:Broadleaf_Dense	2	2	8	8	8	8	9	9	9	9
16:Broadleaf_Open	2	2	2	8	8	8	9	9	9	9
17:Mixedwood_Dense	2	2	2	2	8	8	9	9	9	9
18:Mixedwood_Open	2	2	2	2	2	2	9	9	9	9
19:Mixedwood_Sparse	2	2	2	2	2	2	9	9	9	9

Each cell in the table shows the fuel code assigned for the probability class.