FINAL REPORT

Understanding Pre-Industrial Landscape Patterns on the Upper Peace Region of Alberta

Final Report

fRI Research Healthy Landscapes Program

January 20, 2020

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fRI Research
Informing Land & Resource Management

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ACKNOWLEDGEMENTS

This project is a sub-project of the LandWeb initiative via the fRI Research Healthy Landscapes Program and funded by the Government of Alberta.

Many thanks to the LandWeb funding partners, including West Fraser Timber Co., Alberta Newsprint Company, Alberta Pacific Forest Industries Inc., Mercer Peace River Pulp Ltd., Weyerhaeuser Company, Millar Western Forest Products Ltd., Tolko Industries Ltd., Canfor Company, Louisiana-Pacific Corporation, Mistik Management Ltd., Vanderwell Contractors Ltd, Ducks Unlimited Canada, the government of Alberta, the government of Saskatchewan, and the government of the NWT. Thanks also to the Forest Resource Improvement Association of Alberta (FRIAA) for their generous support as well.

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EXECUTIVE SUMMARY

This project was a spatial modelling exercise that created coarse-scale, pre-industrial landscape metrics for the Upper Peace region of Alberta. The primary goal was to understand if, or in what ways the current condition of the Upper Peace aligns with the historical range. The results suggest that much of this landscape is already beyond its historical range. More specifically, the amount of mature (80–120 years) forest was in most cases already beyond the upper natural range of variation (NRV) threshold and the current level of young (<40 years) forest was close to or beyond the lower NRV threshold. More detailed analyses revealed that the deviation from NRV was more pronounced in those parts of the landscape that were not actively managed for timber, plus those dominated by black spruce. This suggests that wildfire control efforts have been effective for many decades. However, the pattern of high levels of old and low levels of young forest are evident on the 'active' land base as well, suggesting that historical disturbance rates have been higher than harvesting levels over the last few decades.

A large amount of old forest can provide positive benefits to a landscape in the form of a buffer against natural disturbance. On the other hand, the social, ecological, and economic risks of having old forest levels beyond NRV include increased risk of wildfires or insect and disease outbreaks — the impact of which is already evident in BC and Alberta during the 2017 and 2018 fire seasons. Moreover, this study also revealed that the ecological benefits of having large amounts of older forest on this landscape is likely compromised by the cumulative impacts of linear features such as roads, seismic lines, and pipelines rights-of-way that spatially divide what would otherwise be large contiguous patches of old forest into smaller patches.

A less obvious, but equally important implication of the deviation of the study area from NRV is the loss of young forest habitat. While we tend to focus on old forest as the ultimate measure of ecosystem biodiversity, a large number of specialized species are dependent on disturbance, creating a smaller, but unique diversity peak within a few years after fire thanks to the sudden physical, chemical, and environmental changes. This landscape has been experiencing disturbance levels near or at the lower end of NRV for several decades, which minimizes opportunities for disturbance-specialist species.

Of perhaps greater concern is that the shift towards older forest in favour of young forest is a pattern that has been ongoing for many decades. The magnitude and degree of difference right now is such that it would take an increase of several times the current disturbance levels over the next 20 years to just prevent the gap between NRV and current condition from widening further.

Overall, the metrics from this study suggest that this is an unbalanced landscape that is heading in the wrong direction, due largely to decades of the inappropriate use of disturbance as a tool. This is likely already negatively impacting a) resilience (to climate change), b) the likelihood of maintaining a sustainable flow of all goods and services, and c) the risk of natural disturbance agents.

1.0 Introduction

The evolution of forest management in North America has been an ongoing process, but one that has inevitably been moving towards the goal of sustaining all forest values. Forest management is now expected to manage for a wide range of biological values including water and nutrient conservation, toxin filtration, carbon cycling, fish and wildlife habitat, food, pharmaceuticals, and timber (Davis 1993).

Under the auspices of this task, the concept of the using (pre-industrial) forest patterns created by natural processes as management guides is gaining favour in North America (Franklin 1993), and is one of the foundations of an ecosystem-based management (EBM) approach (Booth et al. 1993, Grumbine 1994, Long 2009). The theory is certainly attractive: By maintaining the type, frequency, and pattern of change on a given landscape, we are more likely to sustain historical levels of the various biological goods and services. So called “coarse-filter” knowledge can also be applied directly and immediately to planning and management programs at virtually all levels and spatial scales. Thus, defining the historical range of various ecosystem patterns is a fairly fundamental requirement of a natural pattern-based approach to forest management.

Developing coarse-filter, pre-industrial knowledge is perhaps most challenging at landscape scales. Reliable pre-industrial landscape snapshots are rare to non-existent due to the combined impacts of fire control, cultural disturbance activities, and lack of historical records or data. What we do know about the disturbance history of Canadian boreal landscapes suggests that they are highly dynamic, and the age-class distribution from one time to another can vary widely over time (Turner and Dale 1991, Payette 1993) and space (Andison 1998). This means that historical levels of old forest are likely to be both highly dynamic and spatially variable.

In the absence of detailed and multiple historical data and/or photos, the only means left to capture and explore the dynamics of forest ecosystem patterns at the landscape scale is spatial simulation modelling. In its simplest form, spatial models allow one to explore how known probabilities of key variables intersect in time and over space to create multiple possible landscape scenes or snapshots. When a sufficient number of landscape snapshots have been created by the model, each one is measured to capture the desired metrics, and then summarized to generate the *natural range of variation*, or NRV.

This report summarizes the results of a spatial modelling exercise designed to generate NRV summaries for the Upper Peace region of Alberta.

2.0 Goal

The goal of this project is: ***to understand some simple pre-industrial landscape-scale patterns on the Upper Peace region of Alberta relative to the current condition***. Note that this goal is both narrow (i.e., it will capture only landscape scale patterns) and humble (i.e., it will capture only a small number of simple metrics).

3.0 BACKGROUND

3.1 LANDWEB

This project is a pilot study of a larger Healthy Landscapes Program (HLP) initiative called LandWeb (Landscape Modelling in Western Boreal Canada). The objectives of LandWeb are to a) **Define the historical range of disturbance regimes and landscape conditions for western boreal Canada**, and b) **Create a spatial modelling framework for future scenario and hypothesis testing across western boreal Canada**. The ultimate goal of the larger project is improve the best available science and tools for defining landscape-scale benchmarks of NRV.

The study area for LandWeb (Figure 1) includes 15 partners across five provinces and territories. The study area covers the western-most 125 million ha of the Canadian boreal forest extending west from the Rocky Mountains to the Manitoba border in the east, and from the southern boundary of the forest-grassland interface to the south to the 62nd parallel into the NWT. The area includes 73 million ha of the Boreal Plain ecozone, 25 million ha of the Taiga Plain, 20 million ha of the Boreal Shield, and 7 million ha of transitional areas of the Prairie, Montane Cordillera, Taiga Shield and Boreal Cordillera (Wilken 1986) (Figure 1).

Figure 1. Map of the LandWeb Study Area (shown by the blue dashed line).

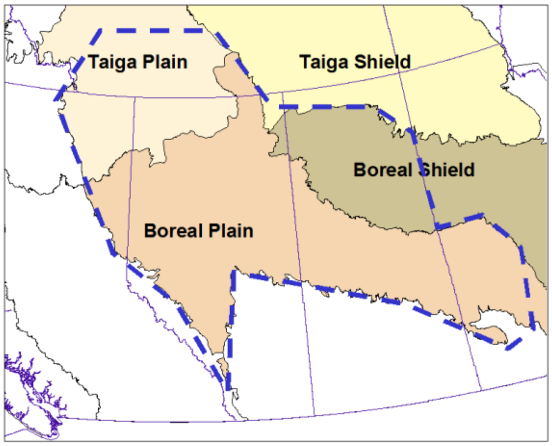
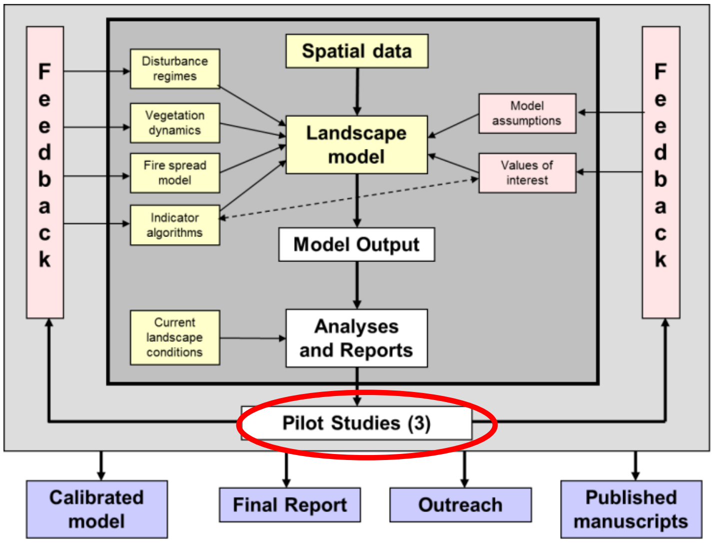


Figure 2. Overview of LandWeb Project Elements.



Yellow boxes = science. Pink boxes = partner input. White boxes = busy work.
Dark gray box = "the model". Light gray box = the process of this project
Blue boxes = deliverables

LandWeb has several linked research elements (Figure 2), all of which are built around the idea of creating a *modelling framework* within which existing or new data, models, or output modules can be inserted, removed, or traded for others. So LandWeb is not a model *per se*, but rather a *modelling configuration*.

The larger framework within which the LandWeb configuration resides is called SpaDES (Spatially Discrete Event Simulator). SpaDES is not a model either, but rather a smart modelling environment within which new and existing model modules and datasets can communicate with each other (Chubaty and McIntire 2018). For example, a fire spread module from model A could be linked to the succession module from model B or C, and datasets from models D and E. Krueger et al (2012) refers to this approach as *ensemble modelling*.

As one (of potentially dozens of possible) configuration of SpaDES, it was recognized that multiple iterations of LandWeb would likely be developed over time, each one adding layers of sophistication, ease of use, or robustness as the case may be. However, the original vision of the very first version of LandWeb was modest and simple. It included largely empirical modules that would be relatively easy to develop and calibrate, including input data, output formats, and the assumptions and drivers behind both fire dynamics and forest succession. The presumed advantage of simplicity in this case was the speed with which such models could be built and run. In support of this vision, the part of LandWeb that determines the frequency, size, shape, severity, and location of fires (i.e., the fire regime) was originally assumed to be largely *input data*, as opposed to having these attributes "emerge" from a more process-based model architecture (as per Figure 2). This assumption thus required defining regime parameters for the entire 125 million ha study area.

This project, and the associated modelling architecture and assumptions, preceded Version 1.0 of LandWeb. The value of this particular pilot study to the greater LandWeb project was both a) to provide specific LandWeb partners with results sooner, and b) to develop and test techniques for dealing with the complexities of multiple regime zones in a spatial model.

4.0 Study Area

The study area for the project was the entire Upper Peace region of Alberta, covering over almost 7.5 million hectares (Figure 3).

Figure 3. Study area: The Upper Peace region of Alberta.

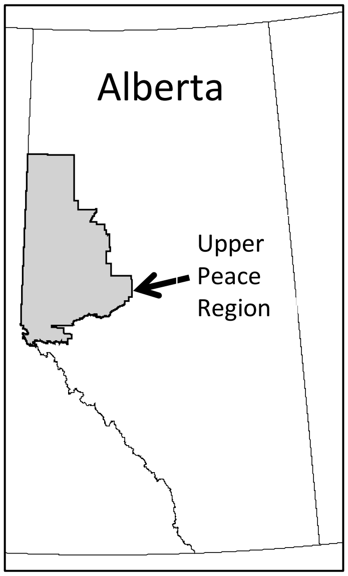


Table 1. Summary of Upper Peace region by leading species

Leading Species	Area	
	Hectares	%
Pine	991,484	13
White Spruce	585,180	8
Black Spruce	711,728	10
Deciduous	2,765,736	37
Mixedwood	587,040	8
Unknown	298,676	4
Total forested	5,939,844	80
Non-forested	1,485,739	20
TOTAL	**7,425,583**	**100**

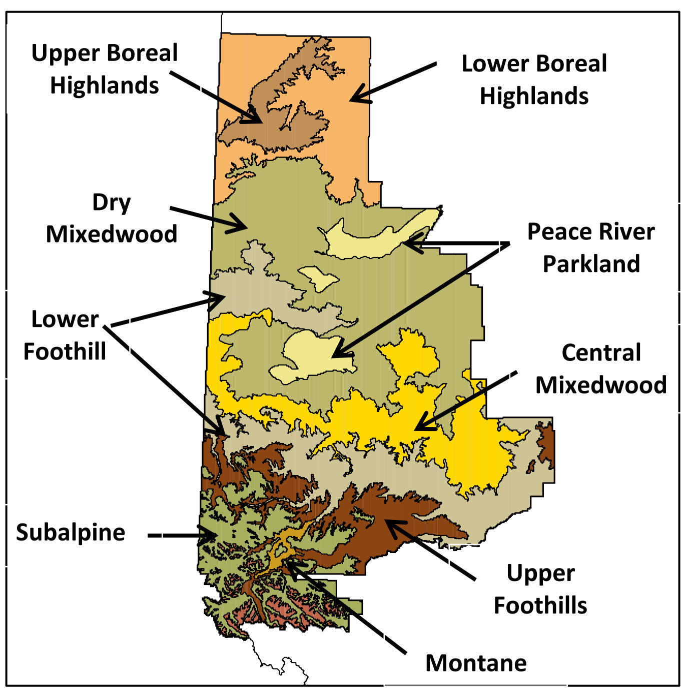
Of the total area in the Upper Peace region, almost 1.5 million ha, or 20% is non-forested. The vast majority of the forested areas are deciduous leading (37%), followed by pine leading forests (13%), black spruce (10%), white spruce (8%) and mixedwood (8%) (Table 1).

Table 2. Summary of Upper Peace region by Natural Sub-Regions (NSR)

NSR Name	Area	
	hectares	%
Alpine	159,327	2
Central Mixedwood	999,544	13
Dry Mixedwood	2,128,088	29
Lower Boreal Highlands	890,367	12
Lower Foothills	1,259,827	17
Montane	48,397	1
Peace River Parkland	307,275	4
Subalpine	662,669	9
Upper Boreal Highlands	290,340	4
Upper Foothills	679,749	9
TOTAL	**7,425,583**	**100**

Ecologically, most of the study area includes the Dry Mixedwood Natural Subregion (NSR) (30%), followed by the Lower Foothills (17%), Central Mixedwood (13%) and the Lower Boreal Highlands (12%) (Table 2). Combined with smaller portions of the Alpine, Montane, Peace River Parkland, Subalpine, the Upper Boreal Highlands and the Upper

Figure 4. Map of the Alberta Natural Subregions (NSRs) in the study area



Foothills NSRs, the Upper Peace is a highly complex region ecologically (Figure 4).

The range of ecological conditions in the study area is noteworthy and highly relevant to the modelling and NRV estimates. The more than 7.4 million ha study area is a relatively large area, which is a beneficial attribute for spatial modelling. However, the Upper Peace ranges from 200–3750 m in elevation, 300–1350 growing degree days, mean annual precipitation from 450–1000 mm, and flat to vertical topography (Table 3). Historical vegetation cover ranges from grassland to grassland open forest to dense closed forest, to open and closed shrubs. In other words, this is by no means a homogenous study area in terms of either biotic or abiotic elements. By association, is it also likely not homogeneous in terms of historical (or future) fire behaviour or risk. In fact, the historical long-term fire cycle estimates for the study area range from 30 to (more than) 250 years (see below). Moreover, these different fire regime zones align strongly with changes in many critical wildfire behaviour elements. For example, shorter fire cycles are associated with low elevation (i.e., higher lighting ignition probability), longer growing (and fire) seasons, and more flammable fuel types. Moreover, the fact that this study area includes so many ecotones (i.e., transition zones between major ecological types) is important to keep in mind.

Table 3. Summary of the biotic and abiotic conditions across the Upper Peace Region.

Natural Region	Natural Subregion	Elevation	Topography	Climate	Vegetation	Soils	Growing Degree Days >5°C	Mean annual Precip (mm)	Relative Summer Moisture Index
Rocky Mountain	Alpine	1900-3650m	Steep to vertical	Abbreviated, cold summers, long, cold, snowy winters	Occasional shrubs, no trees	Non-soil, with some brunisols and regosols	300	1000	0.8
	Subalpine	1300-2300m	Rolling to very steep	Very short cool wet summers, long snowy winters. Highly variable microclimate	Closed Pl forest (low el) opening to mixed Se, L, and Abies forest & krummholz (high el). Wetlands and open water uncommon	Brunisols, with some regosols and non-soil	800	760	1.7
	Montane	825-1850m	Flat mountain valleys to moderate slopes	Cool summers, warm winters. Microclimate important	Closed mixed Pl, Sw, or At forest and grasslands (low el) to Pl forest (high el). Small area in wetlands and open water.	Brunisols, with some chernozems, luvisols and gleysols	1000	590	2.8
Foothills	Upper Foothills	950-1750m	Rolling to steeply sloped	Short wet summers, snowy cool winters	Dense Pl forest (low el) to dense Sb, Sw forest (high el). Small area in wetlands.	Luvisols, with some brunisols	900	650	2
	Lower Foothills	650-1625m	Gently rolling with plateaus	Short summers with average precip, colder very snowy winters	Highly variable. Mostly mesic dense mixedwood forest (At, Pl, Sw, Pb, Ta, Fir, shrubs). Very little water or wetlands	Luvisols, with some brunisols	1100	590	2.7
Parkland	Peace River Parkland	300-800m	Gently rolling plains with some steep riparian slopes	similar to central parkland	Prarie grasslands, with some At. Small areas of wetlands	Chernozems, with some solonetzics	1350	450	4.6
Boreal Forest	Dry Mixedwood (Peace)	225-1225m (lower El in the Peace)	Level to gently rolling plains	Long, warm, dry summers, mild winters	At dominated, with some Sw, shrubs, and fens	Luvisols, with some solenetzics, gleysols, and organics	1300	475	4.1
	Central Mixedwood	200-1050m (lower El in the Peace)	Level to gently undulating	Short warm, moderately wet summers, long cold winters.	Upland mixedwood, Sw, Pj (50%) and Sb fen forests + wetlands (50%). Open water common	Luvisols with some brunisols and organics	1250	500	3.8
	Lower Boreal Highlands	400-800m (in the Peace)	Lower slopes and level plains	Short summers with average precip, cold snowy winters	Diverse forests of At, Pb, Bw, and Pl with fens and bogs. Very little open water	Luvisols with some regosols and Organics	1050	525	3.3
	Upper Boreal highlands	650-1150m	Upper slopes and plateaus	Short, cool, wet summers with cold, snowy winters	Coniferous forests (Pl-Pj, Sw, Sb) with extensive wetlands	Luvisols with organics and gleysols	950	560	2.8

In terms of forest management, almost half of the area of the Upper Peace falls under one of 11 different forest management agreement (FMA) areas (Table 4). The other half of the study area largely falls under the jurisdiction of the provincial government.

Figure 5. Map of the major FMA areas in the study area

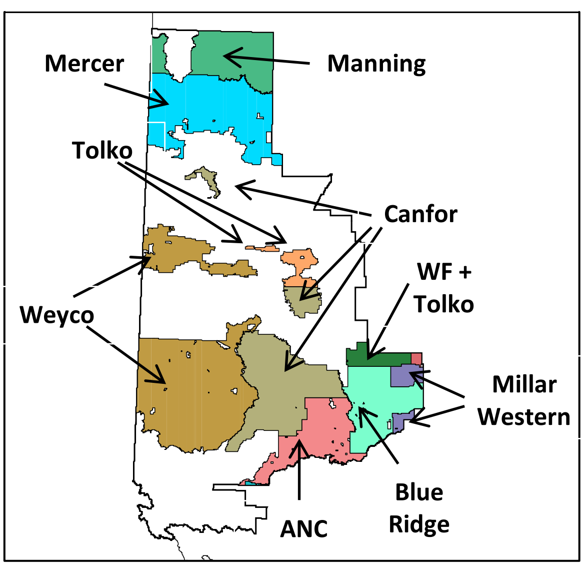


Table 4. Summary of the FMA tenures in the study area by area and name.

FMA Area	Area	
	Hectares	%
Weyerhaeuser Company (Grande Prairie)	1,117,300	30
Canadian Forest Products	644,700	18
Mercer Peace River Pulp (West)	631,800	17
Manning Forest Products	364,900	10
Blue Ridge Lumber	334,400	9
Alberta Newspring Company	329,700	9
Tolko Industries (High Prairie)	79,200	2
West Fraser & Tolko Industries	77,800	2
Millar Western Forest Products	73,100	2
West Fraswer Mills (Slave Lake)	10,100	0.3
West Fraswer Mills (Hinton)	3,800	0.1
TOTAL	**3,666,800**	**100**

The spatially fragmented pattern of FMA tenure areas across the Upper Peace is a good indication of the spatial diversity of ecological conditions (Figure 5). In other words, the blank areas of Figure 5 within the Upper Peace study area were never, nor are they now, thought to be able to produce a long-term sustainable supply of timber.

5.0 Methods

5.1 Modelling Pre-Industrial Landscapes

At the heart of any attempt to generate pre-industrial landscape conditions is the formulation of and assumptions required within a spatially explicit model. Thus, the defensibility of the output is intimately linked with the defensibility of the input mechanism (i.e., model), and the associated modelling assumptions. The model used to create multiple historical landscape scenes for this project was Landmine (Andison 1998).

Landmine is a spatially explicit, cellular automaton, Monte-Carlo landscape simulation model that was developed for landscapes dominated by stand-replacing disturbance events (Andison 1998). Landmine uses a dispersal algorithm to spread fires from one pixel to another in such a way that fire movement responds probabilistically in response to various input layers such as fuel-type, topography, and wind. Fire movement thus favours uphill movement, older forest, high percentages of conifer forest, prevailing winds, or other factors as defined by the user. Controlling layers can be added or removed depending on available data. The nature of the fire movement can also be calibrated to create different fire shapes and residual numbers, sizes, and locations to match empirical data as available. Fire size is controlled by an equation that represents the actual fire size distribution for each landscape. Ignition location probabilities can also be calibrated, often using historical lightning probabilities or pre-defined long-term-fire-cycle (LTFC) estimates. Finally, the total amount of forest burnt in any single time step (10 years in this case) is established through another probabilistic equation capturing the range of historical areas burned (in hectares).

Each of these steps is stochastic, meaning that Landmine never burns the same way twice. However, over the long term the output is consistent with internally defined probabilities. Clarke et al. (1994) also demonstrated that this method of growing disturbances created fractal images, meaning that the model could use spatial data at any scale of resolution. Finally, a succession module is available that includes a set of self-defined rules that governs successional pathways either probabilistically or deterministically depending on stand composition and age (Andison 1996).

In summary, Landmine is a powerful landscape *disturbance pattern model* (*i.e.*, it is good for exploring long-term disturbance regime trends over space and time). It is not meant to predict the patterns or spread of individual fire events. Landmine was developed in 1996 (Andison 1996), and has since been used eight times across Canada.

5.1.1 Model Assumptions

By definition, a model is simple, incomplete representation of reality (Hammah and Curran 2009). There is a trade-off between complex models and simple ones. The “best” model is not necessarily the most complex or realistic one, but rather the one that best suits the purpose. A necessary rule for any modelling exercise is, *as complex as necessary, but no more*. In other words, each modelling exercise should focus on achieving the desired objectives with the least possible number of explanations, equations, and assumptions (Hammah and Curran 2009). In this case the modelling objectives were simple and general in nature;

1) To define the pre-industrial (NRV) percentages of each (of four) seral-stages in each (of five) major vegetation types for each of the following geographic areas:
    - The Upper Peace area as a whole,
    - The provincial natural subregions,
    - Woodland caribou range boundaries,
    - Primary and secondary grizzly bear habitat, and
    - Active versus passive land base
2) To define the pre-industrial (NRV) densities of old forest patches for a) all old forest combined, and b) old forest of the major forest types for any and all patches smaller than 100 ha, between 1–500 ha, larger than 1000 ha and 5000 ha.

Since the interest is in very broad patterns over hundreds of years, Landmine was run with minimal rules and assumptions. No topographic data were included and broad seral-stage and cover-type classes were adopted (see below). Furthermore, succession rules were turned off, and 400 years was adopted as a universal age at which any surviving pixels automatically convert to year zero based on the assumption that over such a long period of time, such areas would be subject to other disturbance agents such as pathogens, disease, wind, snow, or ice.

The most notable modelling assumption was ignition probability, which determines the average long-term fire frequency. The average, pre-industrial long-term-fire-cycle (LTFC) for the entire western Canadian boreal was determined by a combination of a literature review, a two-day workshop of fire regime experts, and another four years of collaboration among fire regime experts. For a full description and explanation of the development of the western boreal pre-industrial LTFC map(s), see Andison (2019).

5.2 Spatial Data

Landmine used a number of spatial data layers for both input and output, each one using 4 ha pixels (200 m square).

5.2.1 Pre-industrial Vegetation

Since the model runs capture NRV, they must represent "natural" (i.e., pre-industrial) landscape conditions with no obvious cultural features such as towns, roads, harvesting, or even fire control impacts. The elimination of the cultural influence on the spatial dataset required three steps.

1) *Create a single landscape snapshot with no cultural features*. The timing or date of this particular landscape was unimportant (see step two ahead). To create a pre-industrial landscape, we first obtained the oldest digital version of forest inventory (with the least amount of cultural disturbance) for each jurisdiction. Then we used available digital data, records, and maps to replace existing cultural features with the attributes of the known pre-disturbed vegetation

types. Any remaining culturally modified polygons were filled in with the age and cover-type attributes of the adjacent polygon with the greatest length shared boundary. Thus, all towns, roads, cutblocks, mines, and other human developments were replaced by attributes of the last known, or the most likely, polygon.

2) *Create an unbiased starting point for the model*. The "natural" pre-industrial snapshot created in step one may still include bias or inaccuracies from a) fire control b) using data from different eras, or c) aging errors from forest inventories, all of which could influence the subsequent model output for several centuries. To eliminate this risk, the model was run forward in time a minimum of 1000 years before landscape snapshots were collected and measured for NRV.

3) *Stratify the vegetation into major vegetation types*. The inventory data was used to define one of five forest cover-classes, as per GoA's direction:
    a. Pine leading
    b. White spruce leading
    c. Black spruce leading
    d. Hardwood leading
    e. Mixedwood leading

Note that if a polygon had a leading tree species, it was modelled regardless of whether or not it was productive, or 'active' forest. Non-forested land was included as a fuel type in the model, but not tracked and summarized for the output.

Age data were used to define four broad *seral* stages of stand development. The Alberta government (GoA) proposed four universal seral-stages, as follows:

- Young ≤ 40 yrs.
- Immature = 41–80 yrs.
- Mature = 81–120 yrs.
- Old ≥ 120 yrs.

5.2.2 Current Condition

The spatial data used to calculate current conditions for the various metrics were the most recent Alberta Vegetation Inventory (AVI) data for the study area. These data were provided by the Alberta government, plus the most recent AVI data for the eleven FMA tenure-holders for the study area. The area in each of the four seral-stages × five major vegetation types (as described above) were queried in ARC GIS using the same rules for defining each strata as used by the model. The calculation for the current condition for patch size included using any and all linear features available in the same AVI dataset.

5.3 Model Calibration

The calibration required for this particular set of Landmine runs is largely related to fire regime attributes. A *fire regime* is a description of how often, how large, and how severe fires occur, and other details about seasonality and location. Fire regime attribute combinations tend to be landscape unique, and linked to major ecological, vegetation, topographic, and climate factors. For example, there tends to be an inverse relationship between fire frequency, and fire size and severity (e.g., Falk et al. 2007, Steel et al. 2015). As part of the larger LandWeb project, an expert workshop and series of subsequent collaborative interviews suggests that the larger Upper Peace region of Alberta has ten distinct fire regimes (Andison 2019), which suggests a highly complex local fire history.

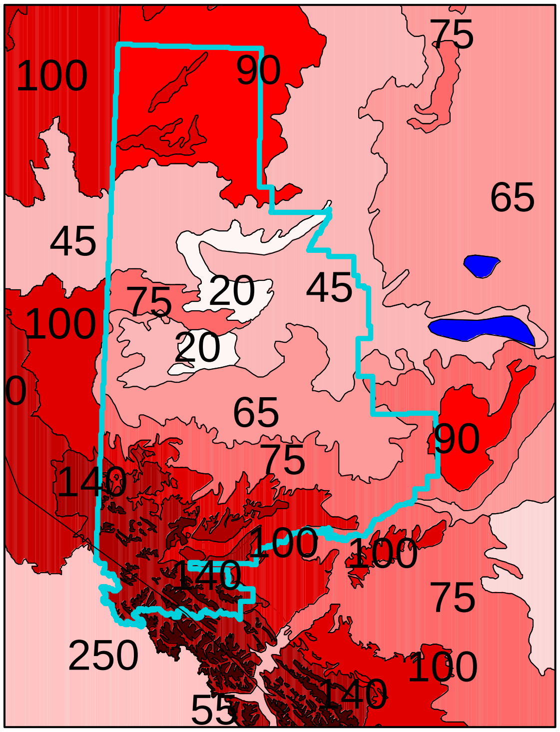
5.3.1 Fire Frequency

The frequency of disturbance can be captured in several different ways. At very broad scales, the long-term (average) *fire cycle* (LTFC) is the average number of years required to burn an area equivalent to the study area. Note this is not the number of years to burn the entire study area — just the equivalent number of hectares burned over time. For example, on a 100 000 ha study area, how many years (on average) does it take for the total area burned by all fires to add up to 100 000 ha? Thus, during any given fire cycle, some areas will burn more than once, and others not at all.

Based on an earlier version of the LTFC map generated by the fire regime workshop and subsequent solicitation process (Andison 2019), the overall average fire cycle for the study area is almost 73 years (derived from the data from Andison (2019) overlain with the Upper Peace study area). Yet, the same expert process determined that the LTFCs in the study area ranged from 30–140 years (Figure 6).

Note that the final V4.0 LTFC map generated by the expert process was an earlier version of that described by Andison (2019) and differs from Figure 6 in two ways. First, the Dry Mixedwood NSR area LTFC as 45 years in the final Andision (2019) report instead of 60 years. The second difference is that the LTFC for the Peace River Parkland NSR LTFC was 20 years in the final report instead of the 30 year assumption used here. The influence of these changes on the modelling results in this study are negligable. Neither of these two NSR areas currently has substantial forested areas, and little if any of the FMA areas include areas from either NSR.

Figure 6. Long-term-fire-cycle (LTFC) estimates (in years) from expert advice and input.



Using the average LTFC estimates in the model directly would be inappropriate. We know that long-term fire cycles vary in important ways over years, decades, and centuries. Thus, the model required an equation representing probabilities of different fire activity levels over time. In this case, decadal variability in the LTFC was captured by an equation representing decadal levels of historical fire activity in the Alberta foothills using a back-casting technique (*sensu* Vilen et al. 2012) that peels back the most recent age-class, and assumes that the age of the forest underneath is proportional to the age-class distribution of the remainder of the landscape. It is important to keep in mind that the precision of this process (representing past disturbance levels) is not critical. The only function of this model parameter is to approximate historical levels of ***variability*** around the LTFC, not the LTFC itself.

The next step was to calibrate the model output LTFCs with the targets defined for each NSR (i.e., regime) from the historical fire regime estimates from Andison (2019). This was accomplished by adjusting fire ignition probabilities in each fire regime zone using the statistical ignition probabilities as the starting point based on LTFC alone. The focus of this part of the model calibration was getting the numbers in the *LTFC Achieved in Model* column to match those in the *LTFC Targets for Model* column in Table 5. Due to the complexity of the study area, this calibration took more time and effort than anticipated. Study areas with multiple fire regime zones are far more challenging to calibrate for LTFCs because ignition probability alone cannot account for fire activity in that zone. Fires regularly ignite in one area and spread to another, particularly when they are so close to each other geographically. The only way to capture this dynamic is to a) model it in space and time, b) compare results with expectations, c) adjust ignition probabilities, and repeat. After several weeks of this iterative calibration process, 100 landscape snapshots were captured, measured, and summarized to represent NRV (Table 5).

Table 5. Summary of the area modelled in this project, showing how ignition probability was manipulated to achieve the desired LTFC averages.

Natural Sub-Region	Total Land Area		Forest Area							
			Forest			Targets for Model			Achieved in Model	
	Area (ha)	% of Total	Area (ha)	% of Forest	% of Total	% of Ignitions	LTFC (years)	Area Burned per Decade (ha)	LTFC (years)	Area Burned per Decade (ha)
Alpine	159,456	2.1	10,584	0.2	6.6	0.04	300	353	213	496
Central Mixedwood	999,392	13.5	907,796	15.3	90.8	17.1	65	139,661	70	129,749
Dry Mixedwood	2,128,680	28.7	1,595,580	26.9	75.0	32.5	60	265,930	61	263,094
Lower Boreal Highlands	890,636	12.0	769,252	13.0	86.4	12.5	75	102,567	76	101,266
Lower Foothills	1,259,804	17.0	1,134,164	19.1	90.0	18.5	75	151,222	71	159,519
Montane	48,408	0.7	43,652	0.7	90.2	1.2	45	9,700	44	10,031
Peace River Parkland	307,248	4.1	63,744	1.1	20.7	2.6	30	21,248	33	19,567
Subalpine (low elevation)	662,920	8.9	522,544	8.8	78.8	4.7	135	38,707	127	41,065
Upper Boreal highlands	290,384	3.9	276,852	4.7	95.3	3.4	100	27,685	100	27,817
Upper Foothills	680,152	9.2	615,736	10.4	90.5	7.5	100	61,574	96	64,209
TOTAL	**7,427,080**	**100**	**5,939,904**	**100**		**100**		**818,647**		**816,814**

5.3.2 Fire Size

The output from the same LandWeb workshop referred to above concluded that there were not yet enough data or evidence to define or defend specific, unique fire size distributions for the majority of the western boreal (Andison 2019). The expert group did agree on some maximum fire size numbers, but not for all areas of the boreal. The maximum fire size estimates suggested by the experts relevant to this study included 1000 ha in the Peace River Parkland, 3000 ha in the Montane, and 5000 ha in the Dry Mixedwood (Andison 2019).

The strategy to model fire size was to reflect both the agreement on general trends, and that of specific fire regime zone information / knowledge. First, an edited version (accounting for missing small fires and fire control) of the Alberta provincial historical fire database was used to generate the following cumulative equation for fire size, in hectares:

$$FireSize = 10^{\left(1.85\times(-\log(1-RN))^{.65}\right)} - 0.14$$

Where RN is a random number between 0 and 1. This equation allows for a very high probability of very small fires and very low chances of very large ones — consistent with the pattern of fire sizes observed across the majority of the Canadian boreal (Ward and Tithecott, 1993, Taylor *et al.* 1994). The consistency of this pattern across the boreal and among scientists suggests that the details are less important than the trend; very large fires, although rare, are highly influential.

The second layer of filtering of fire sizes included limiting maximum fire sizes in the Peace River Parkland to a maximum of 1000 ha, 3000 ha in the Montane, and 5000 ha in the Dry Mixedwood, as per the fire regime workshop results (Andison 2019).

5.3.3 Fire Severity

One of the strengths of Landmine is the ability of the model to create realistic fire pattern details, including fire shape and residual levels (Andison 1996). However, as with all other fire spread models today, Landmine does not capture partial severity in residuals. Research suggests that partial severity is quite common in natural wildfires accounting for an average of 10% of fire event area in the foothills, and over 25% of fire event area in the boreal plains (e.g., Andison 2004). Landmine was originally calibrated to leave an average of 10% as interior island remnants using the disturbance event definition (*sensu* Andison 2012).

5.4 Running Landmine

For each of the 100 landscape snapshots generated by the model, non-spatial summaries of area each of the five vegetation × four seral stage classes were compiled for a) the entire Upper Peace, b) the natural subregions, c) woodland caribou herd areas, and d) grizzly bear primary and secondary areas. In addition, NRV non-spatial summaries for *active* and *passive* land bases were captured for both the Canfor and Weyerhaeuser FMA areas.

Spatial summaries of each landscape snapshot were captured in the form of old forest patch sizes. Pixel membership in a "patch" of old forest was defined only by immediate adjacency. Thus, any *old* pixel (as per the age rules defined above) will be grouped with any other *old* pixel if it was one of its eight neighbours. If an old forest patch crossed the study area boundary, only that portion of old forest patches within the study area was counted. While this created a negative bias of the actual size of old forest patch sizes regionally, it allowed the output to be compared directly to management planning scenarios applicable to the study area boundaries.

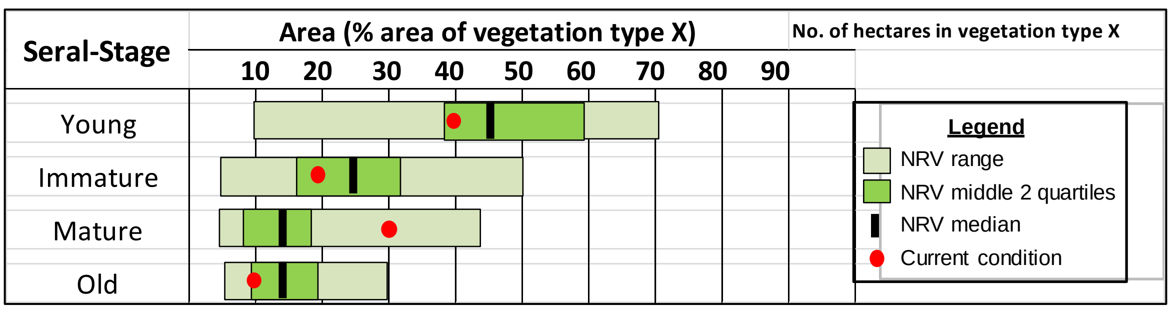
6.0 Results

6.1 Non-spatial Results

The non-spatial results from the NRV modelling results are presented as *quartiles*. As the name suggests, quartiles gather dozens, hundreds, or thousands of measurements into four evenly spaced groups, each one representing 25% of the total number of measurements. So, for example, if the observations of a metric of concern were 2, 3, 4, 5, 9, 11, 16, 23, 25, 26, 27, 30, 40, 50, 70, and 100, the first quartile would be 2–7, the second 7–24, the third 24–35, and the fourth 35–100.

Using quartiles to present the results not only simplifies the output into a more visually intuitive form, but also allows viewing all seral stages of a given vegetation type at the same time. The example shown in Figure 7 reads as follows: First, each set of four quartiles represent all seral-stages of a specific vegetation type X. Recall there are five vegetation types. The associated area (in hectares) of the vegetation type being shown is in the upper right hand corner of each graph in small font. So, if the total area of the veg type is 100 000 ha, and vegetation type X is pine leading, that means there are 100 000 ha of pine leading forest across the four seral-stages.

Figure 7. Example of how the non-spatial modelling results are presented in this report.



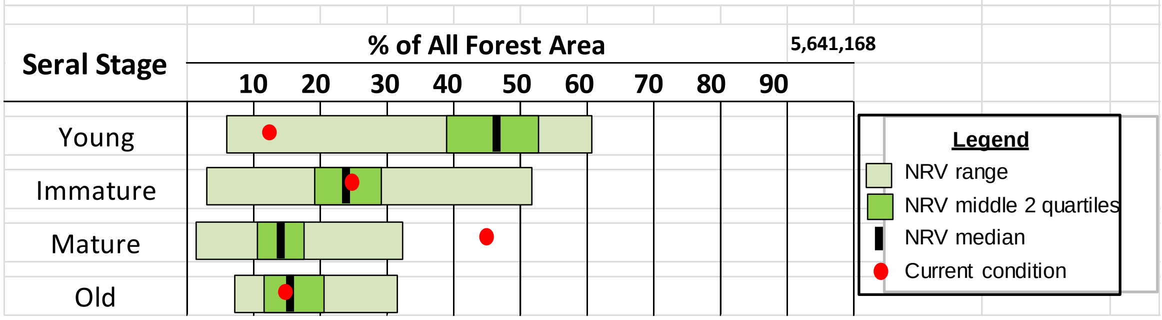
In terms of the details of the graph, the width of the green bands (regardless of shade) captures all 100 model runs representing the true NRV, and the red dot is the current condition. So in Figure 7 the red dot at 40 for *young* forest represents 40% of the 100 000 ha of veg type X — or 40 000 ha. Similarly, the red dots represent 20% (or 20 000 ha) of immature, 30% (or 30 000 ha) of mature, and 10%) or 10 000 ha) of old forest, for a total of 100 000 ha of forest. Thus, the red dots will ***always*** add up to 100%.

The quartiles are represented by the different shades of green. For example, in Figure 7, no model runs created less than 10% and no more than 70% of young pine. The quartiles (bands within which exactly 25% of the data lie) are represented by the different shades of green (Figure 7). Quartiles are numbered in order from lowest to highest. So quartile one (Q1) is the light green band on the far left of each bar, quartile two (Q2) the dark green band immediately to its right, the third quartile (Q3) the second dark green band to the right of that, and the fourth quartile (Q4) the light green band to the far right (Figure 7). The dark black line between Q2 and Q3 is the *median,* which is the 50th percentile of the NRV data. Note that the four medians in each figure will approximately (but not always exactly) add up to 100%.

6.1.1 Upper Peace Overall

Overall, the Upper Peace seral-stage distributions deviated from NRV in important ways. While the current level of old forest was close to the NRV median, the current percentage of mature forest (45%) was well beyond the maximum of 32% observed historically *via* the modelling exercise (Figure 8). However, when mature and old are combined, the current level of 62% was only exceeded once in 100 runs by the NRV model runs — and thus statistically beyond NRV. Similarly, the model simulations created a landscape that had less than the current level of 12% young forest only once out of 100 possibilities. The current level of immature forest in the study area is well within NRV (Figure 8).

Figure 8. Historical Range of All Forest in the Upper Peace

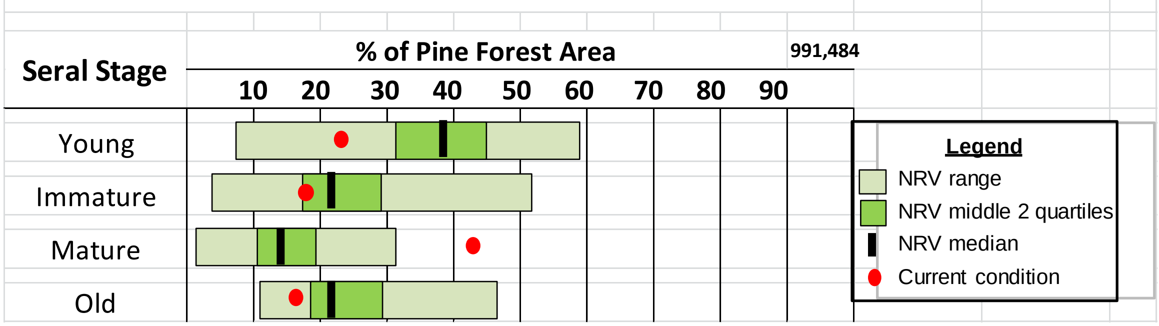


6.1.2 Major Vegetation Types

This section presents the modelling results by the five leading forest types, as defined and requested by the Alberta government (see section 5.2.1).

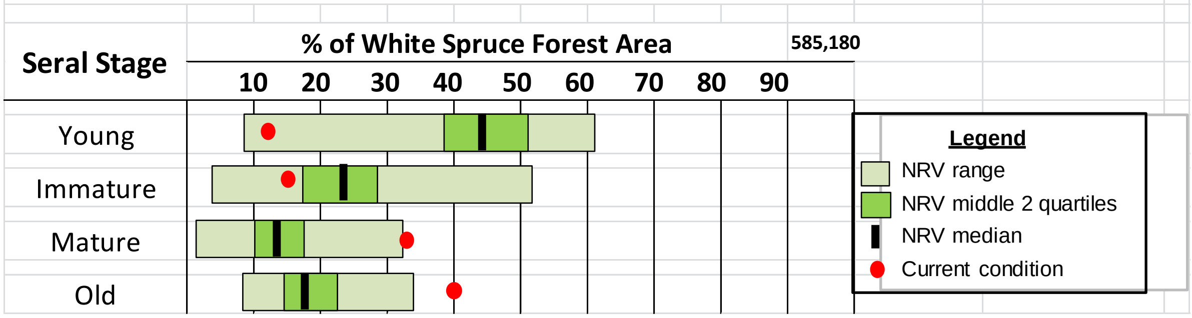
The pattern of current levels of pine-dominated forest levels was similar to that observed overall. Immature and old forest levels were both well within NRV, while the current level of young forest was only at the 10th percentile of NRV. The 43% currently in mature forest was well beyond the upper end of NRV, and more than three times the NRV median (Figure 9).

Figure 9. Historical Range of Pine in the Upper Peace



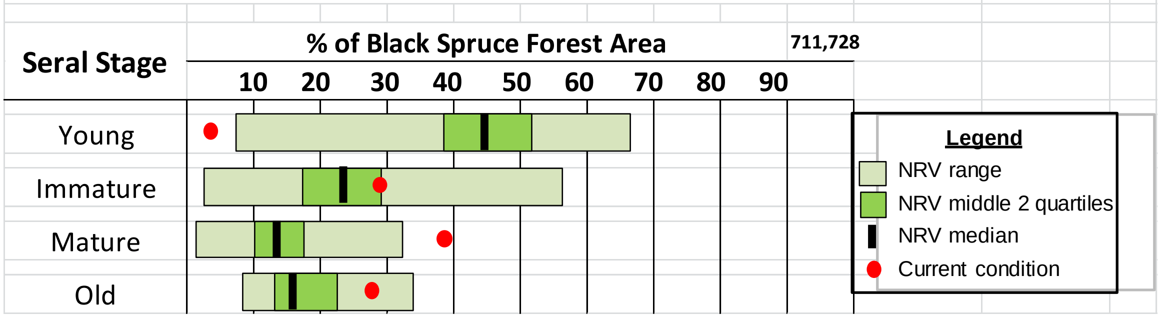
The current level of white spruce dominated forest on the study area had far more older forest than the NRV data suggest for the pre-industrial benchmark. For example, the 40% of old white spruce forest was well beyond the 34% NRV maximum observed, and the current level of 33% mature forest was also beyond anything observed by the NRV landscape snapshots (Figure 10). However, keep in mind that the succession module was turned off in Landmine. When mixedwood forests burn, young stands often start out as hardwood and become mixedwood or white spruce as they age. Thus the modelling results were likely under-estimating the historical levels of old white spruce, which means the deviation between the current and historical old forest levels noted here is likely much smaller.

Figure 10. Historical Range of White Spruce in the Upper Peace



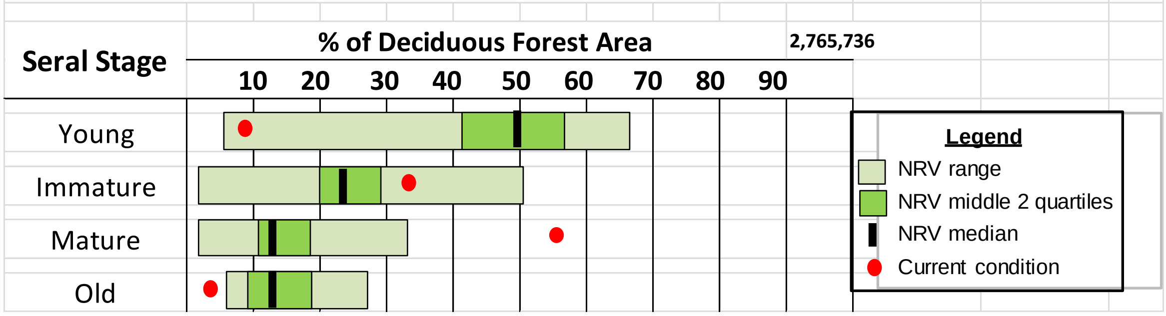
The differences between NRV and current condition for black spruce dominated forests observed on the study area was similar to that previously noted, although to a more extreme degree. The current 4% of young black spruce forest was not only significantly lower than the 45% median, but also well below the 7% minimum observed from the NRV simulation exercise (Figure 11). The observed amount of mature black spruce was also well beyond the maximum level observed by the NRV modelling exercise (39% vs 33%). The main difference is that in this case the current level of old Sb forest (28%) is very close to the upper threshold of NRV (Figure 11).

Figure 11. Historical Range of Black Spruce in the Upper Peace



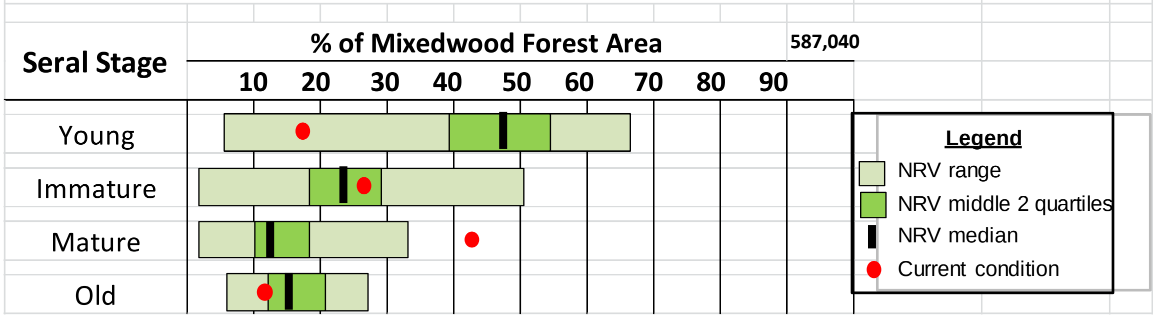
The current level of old deciduous forest observed on the Upper Peace was 9%, which made it statistically unlikely given that a lower level was only observed once in the NRV data (Figure 12). The current level of old deciduous forest was also below the lower threshold of NRV, although the amount of mature deciduous was 56%, which was well beyond the upper range of NRV. This unusual pattern can only partly be explained by the model succession rules. The fact that there was very little old deciduous observed today is likely due to the fact that older stands dominated by hardwood tended to become mixedwood or white spruce as they age. The model thus over-represented historical levels of old deciduous forest. So the deviations noted in Figure 12 between current and NRV conditions are in part due to a model artefact. However, using the same logic, the actual deviation between observed and NRV data for mature deciduous forest can only be larger than shown here.

Figure 12. Historical Range of Deciduous in the Upper Peace



The current levels of mixedwood forest on the study area were similar to those noted overall; immature and old forest were currently well within NRV. The current levels of young forest were very close to the lower end of NRV, and the extremely high levels of mature forest are well beyond NRV (Figure 13).

Figure 13. Historical Range of Mixedwood in the Upper Peace

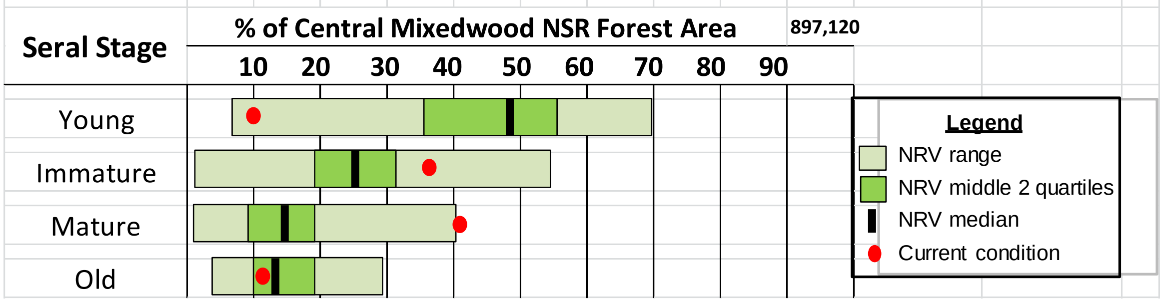


6.1.4 Ecological Natural Subregions

When the results were broken down by the provincial natural subregions (NSRs) they were generally similar to those observed previously, although there were some notable differences.

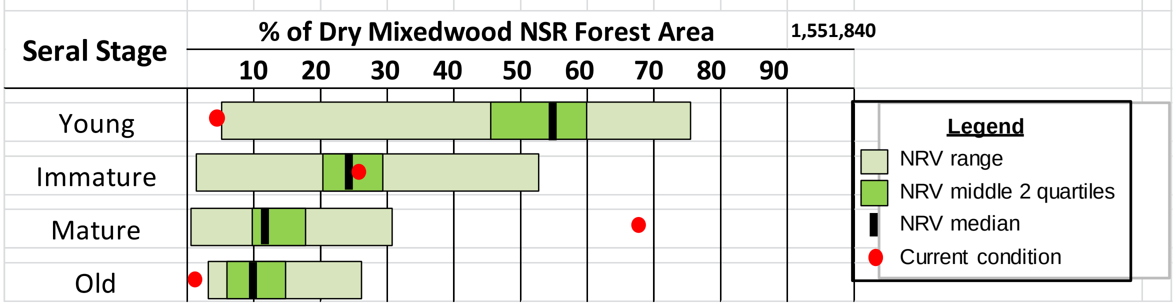
The Central Mixedwood (CM) area had a historical LTFC of 65 years (Table 5), which created a significant amount of young forest. Young NRV in the CM averaged 46% with a median of 48% (Figure 14). The current level of young forest in the CM area was 13%, which represented just the 3rd percentile. The current old forest level (12%) was close to the median NRV level of 13%. However, as previously seen, the current mature forest level (41%) was beyond NRV and almost triple the median NRV.

Figure 14. Historical Range of the Central Mixedwood NSR in the Upper Peace



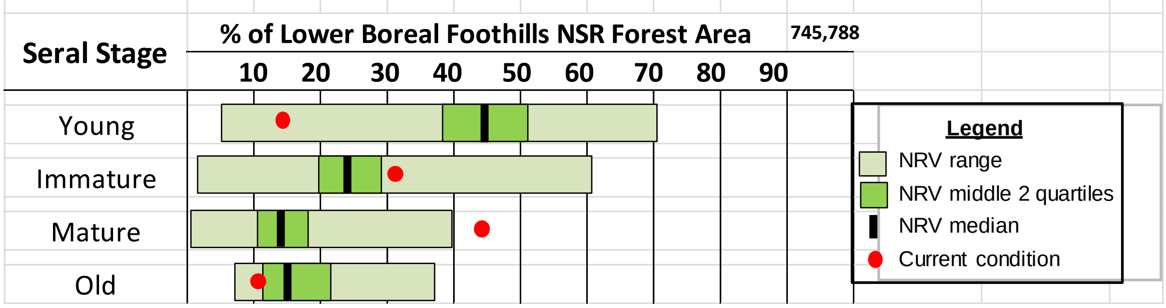
The vast majority (68%) pf the forest in the Dry Mixedwood (DM) NSR is between 80–120 years old (Figure 15). This is not only well beyond the upper boundary of NRV, but it means most of the other seral stage levels were beyond NRV. In fact, although the amount of immature DM forest was near the NRV median, current levels of both the young and old seral stages were not only below the NRV lower boundary, but close to zero. However, a more important difference between historical and current conditions in this case is that the vast majority of the DM in the Upper Peace no longer supports forest.

Figure 15. Historical Range of the Dry Mixedwood NSR in the Upper Peace



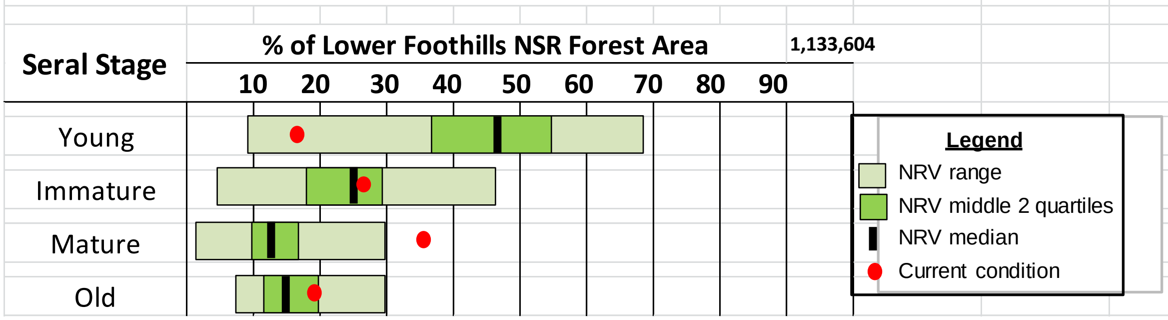
The Lower Boreal Foothills (LBF) part of the study were currently has low levels of young and old forest, and high levels of mature forest relative to NRV (Figure 16). The 15% young forest sits at just the 5th percentile of NRV, and old forest levels current sits at the 12th percentile of NRV. As seen with most other NSRs, the amount of mature forest was beyond the upper boundary of NRV (Figure 16).

Figure 16. Historical Range of the Lower Boreal Foothills NSR in the Upper Peace



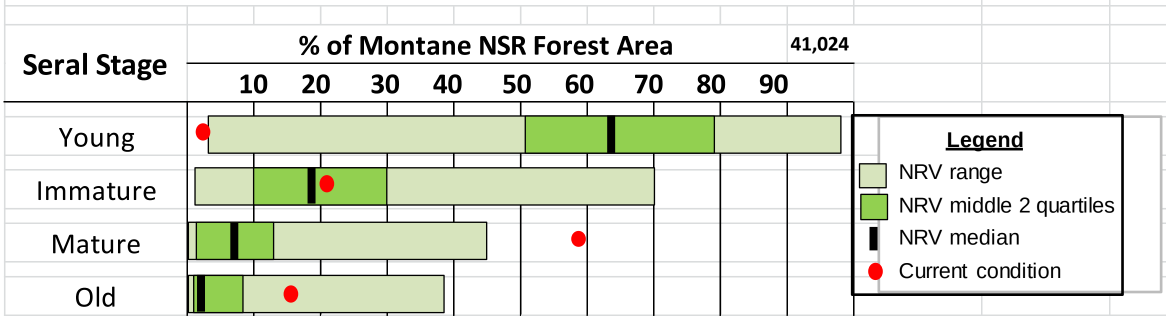
The current seral stage condition of the Lower Foothills (LF) area of the study area revealed patterns similar to those discussed previously. The current level of young forest (17%) was close to the lower end of NRV, the amount of immature forest (28%) was close to the NRV median, the amount of mature forest was beyond the upper threshold of NRV, and the current old forest level was on the high end, but still well within NRV (Figure 17).

Figure 17. Historical Range of the Lower Foothills NSR in the Upper Peace



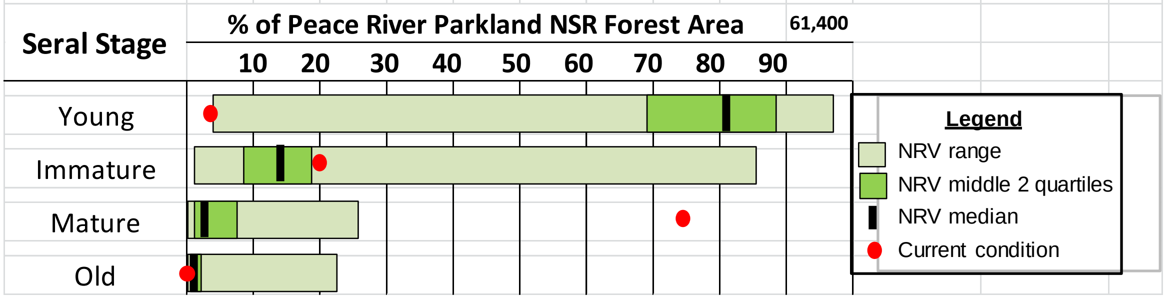
Montane NRV patterns reflected the relatively high level of historical wildfire activity in this area. Young montane (Mont) forest on the study area currently sits at 3%, which is below the lower threshold of NRV, and significantly lower than the NRV median of 64% (Figure 18). The current amount of mature forest was almost 60%, which was significantly more than the median of 7% and maximum of 45%. Old forest was within, but on the high end of NRV. The current level of immature forest in the Lower Foothills was close to the NRV median from modelling (Figure 18). It is also noteworthy that this is the smallest NSR area at just over 41 000 ha.

Figure 18. Historical Range of the Montane NSR in the Upper Peace



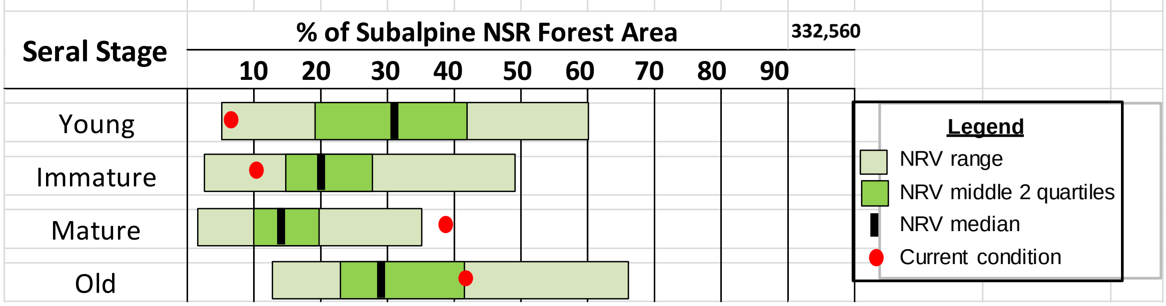
The Peace River Parkland (PRP) had the most frequent fire cycle at 30 years, reflected in extremely high levels of young forest, and very low levels of old forest historically (Figure 19). Currently, almost all of the PRP forest is between 40–120 years of age, and most of that mature. Most of the other seral-stage levels are close to, or beyond NRV. Note also that the PRP was not particularly well represented in the study area (61 000 ha). Having said that, the risk of losing unique habitat in the PRP is extreme.

Figure 19. Historical Range of the Peace River Parkland NSR in the Upper Peace



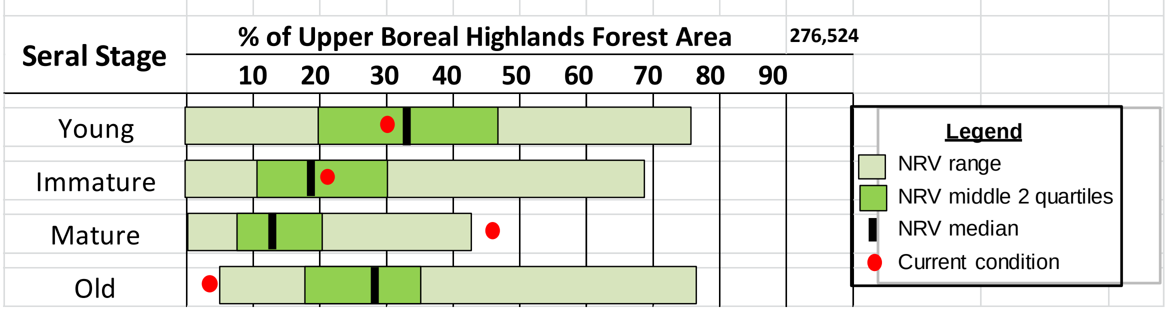
The Subalpine (SA) NSR had a LTFC of 135 years, which generated a relatively large amount of old forest (Figure 20). Nevertheless, the current level of old forest was still well beyond the NRV median, and the amount of mature forest beyond the upper limit of NRV. In contrast, current young forest was statistically lower than the lower threshold of NRV, and the amount of immature forest close to the NRV lower threshold (Figure 20). Together, the 18% of forest <80 years of age was below anything observed historically. In other words, even in that part of the study area with the lowest level of historical wildfire disturbance, there is an imbalance of a) too much older forest, and b) not enough younger forest.

Figure 20. Historical Range of the Subalpine NSR in the Upper Peace



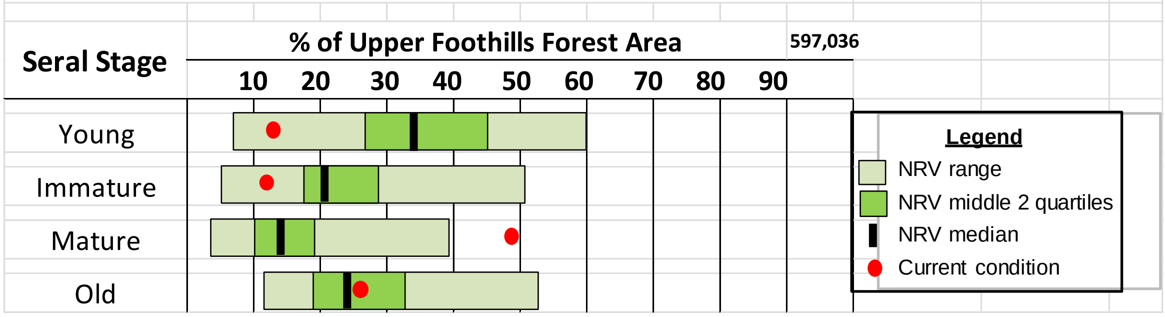
Current levels of forest in the young and immature seral stages of the Upper Boreal Highlands (UBH) NSR were both very close to the NRV median (Figure 21). This is a unique pattern not shown by other NSR areas. However, the amount of mature forest currently sits beyond the upper boundary of NRV, and the current amount of old forest was below the lower boundary of NRV (Figure 21).

Figure 21. Historical Range of the Upper Boreal Highlands NSR in the Upper Peace



The LTFC of the Upper Foothills (UF) NSR is relatively high (i.e., 100 years), which produced a large amount of old forest (Figure 22). And the current level of old forest was consistent with the NRV median. However, the current level of mature forest was well beyond the upper bound of NRV, and the amounts of young and immature forests were both on the low end of NRV (Figure 22). Forest older than 80 years of age (mature + old combined) was currently well beyond anything observed in the NRV data.

Figure 22. Historical Range of the Upper Foothills NSR in the Upper Peace

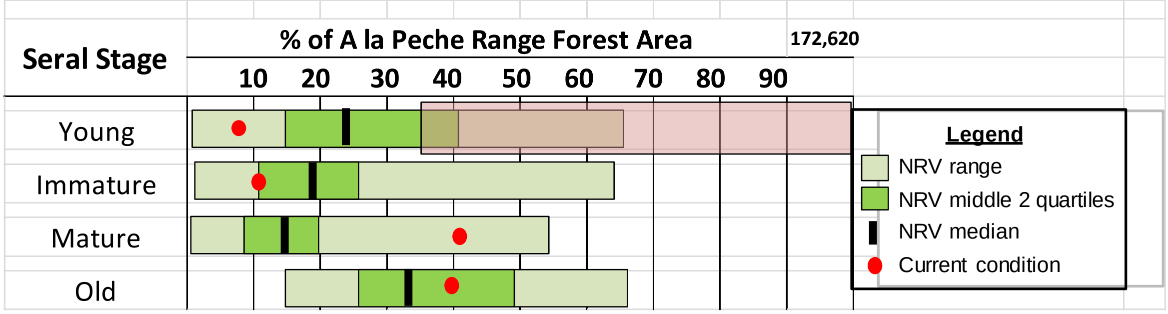


6.1.5 Woodland Caribou Ranges

Five caribou ranges wholly or partly intersect the Upper Peace region; A la Peche, Chinchaga, Little Smoky, Narraway and Redrock-Prairie Creek. Also included in these resulted is the threshold of unacceptable habitat conditions (i.e., more than 35% young forest) for caribou as defined by Environment Canada (2012).

The model generated landscapes that had acceptable caribou habitat conditions 71% of the time for the A la Peche range. The current condition of 8% was within, although on the low end of NRV (Figure 23). In fact all current forest levels in the A la Peche range are within NRV. The concern is that the amount of mature plus old forest was currently on the high end of NRV. When mature and old forest levels were combined, the 81% observed today was only exceeded six times by the NRV modelling exercise (Figure

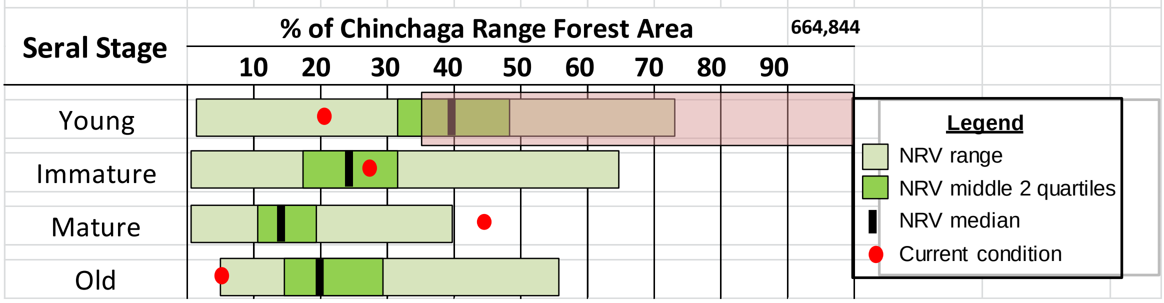
Figure 23. Historical Range of the A la Peche Range in the Upper Peace (the shaded reb box in the young seral-stage represents unacceptable conditions for the survival of woodland caribou by Environment Canada)



23).

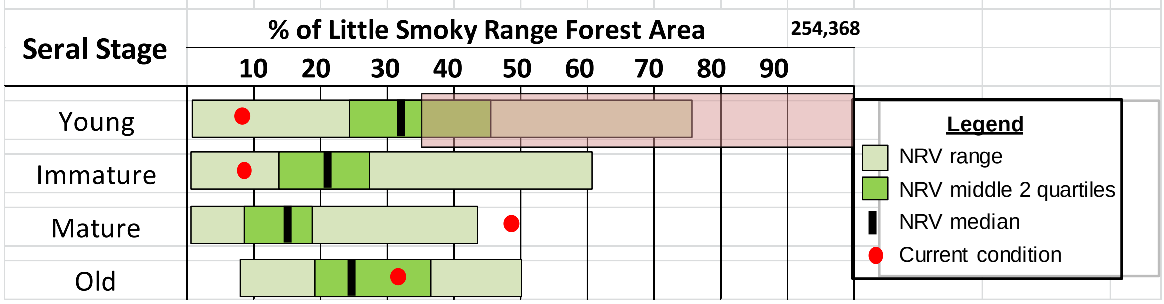
Minimum woodland caribou habitat requirements were met only 31% of the time by the NRV modelling output for the Chinchaga caribou range, although the current level (21%) was well within the acceptable range (Figure 23). Current levels of mature forest (46%) were well beyond the upper boundary of NRV, while the current level of old forest was statistically below the NRV lower threshold. The current amount of immature forest was on the boundary between the 1st and 2nd quartile (Figure 23).

Figure 24. Historical Range of the Chinchaga Range in the Upper Peace (the shaded reb box in the young seral-stage represents unacceptable conditions for the survival of woodland caribou by Environment Canada)



The model generated acceptable caribou habitat conditions 60% of the time for the Little Smoky caribou range, and the current level of 8% young forest was well below the 35% maximum threshold (Figure 25). Otherwise, ***the forest in the little smoky range is highly imbalanced relative to NRV***. Forest under 80 years of age (i.e., young plus immature) accounted for only 18%, which was never observed historically. In fact, the least amount of forest <80 years of age observed from the NRV data was 32%. The very low levels of both young and immature forest only support this (Figure 25).

Figure 25. Historical Range of the Little Smoky Range in the Upper Peace (the shaded reb box in the young seral-stage represents unacceptable conditions for the survival of woodland caribou by Environment Canada)



Acceptable levels of young forest for the Narraway range occurred only 41% of the time historically (Figure 26). As above, the amount of forest currently younger than 80 years is well below any of the possible landscape scenes generated by the model (Figure 26).

The historical landscape data for the Redrock-Prairie Creek caribou range created no more than 35% of young forest 55% of the time, and the current level is just 2% (Figure 27). In contrast, the forest <80 years of age in the Redrock-Prairie Creek range historically averaged almost 50%. The 16% of Redrock-Prairie Creek forest <80 years of age was ***never*** observed historically. Similarly, the 84% currently sitting in forest >80 years of age is well beyond anything observed historically.

Figure 26. Historical Range of the Narraway Range in the Upper Peace (the shaded reb box in the young seral-stage represents unacceptable conditions for the survival of woodland caribou by Environment Canada)

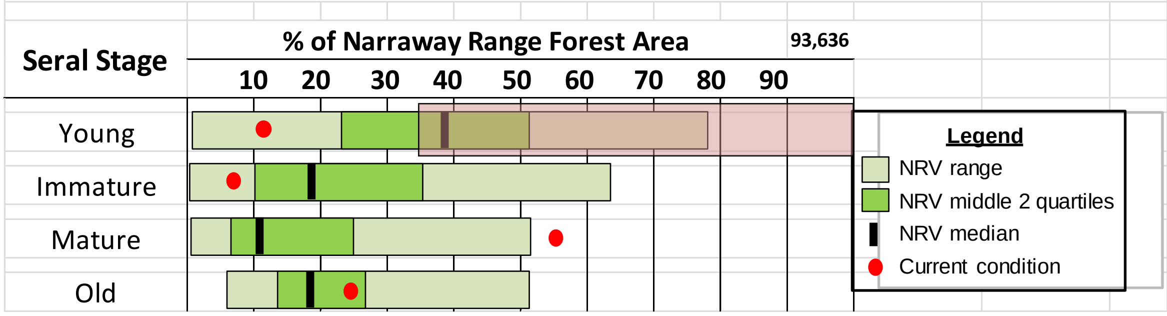
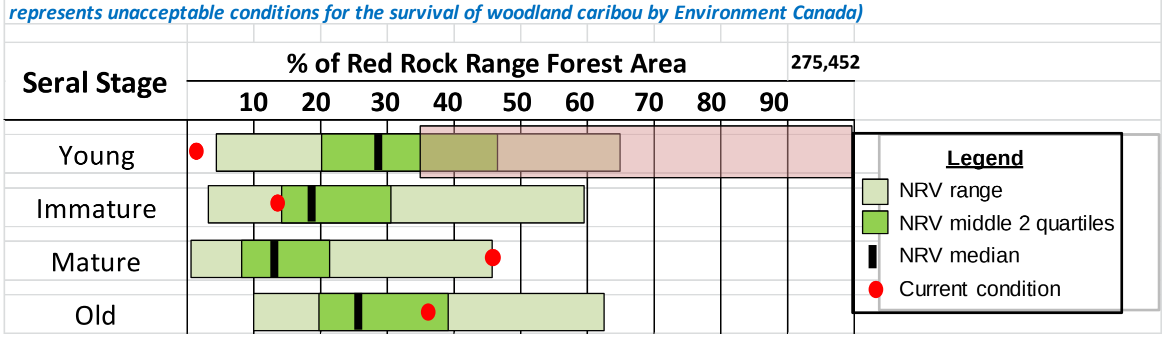


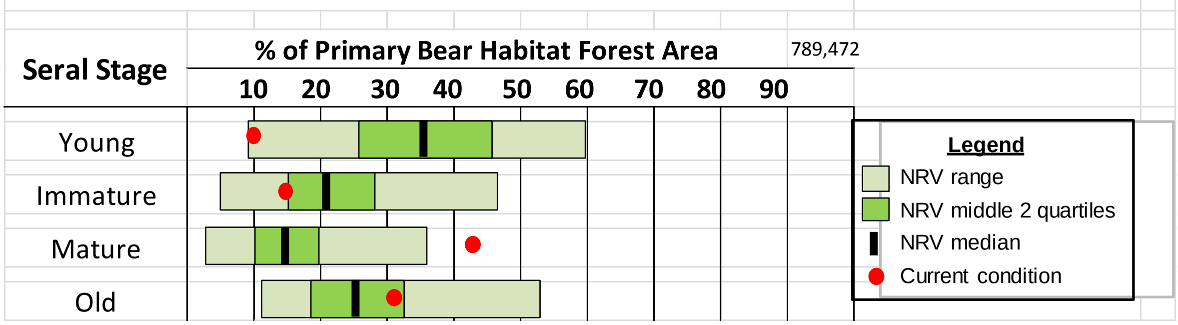
Figure 27. Historical Range of the Red Rock Range in the Upper Peace (the shaded reb box in the young seral-stage represents unacceptable conditions for the survival of woodland caribou by Environment Canada)



6.1.6 Grizzly Bear Habitat

The Upper Peace has almost 790 000 ha of primary grizzly bear habitat and another 1.6 million ha of secondary habitat. The seral-stage patterns relative to NRV of both were much like that of the overall landscape. Observed young forest levels were close to or beyond the lower bound of NRV, and mature forest levels were beyond the upper NRV threshold (Figures 28 and 29).

Figure 28. Historical Range of Primary Grizzly Bear Habitat in the Upper Peace

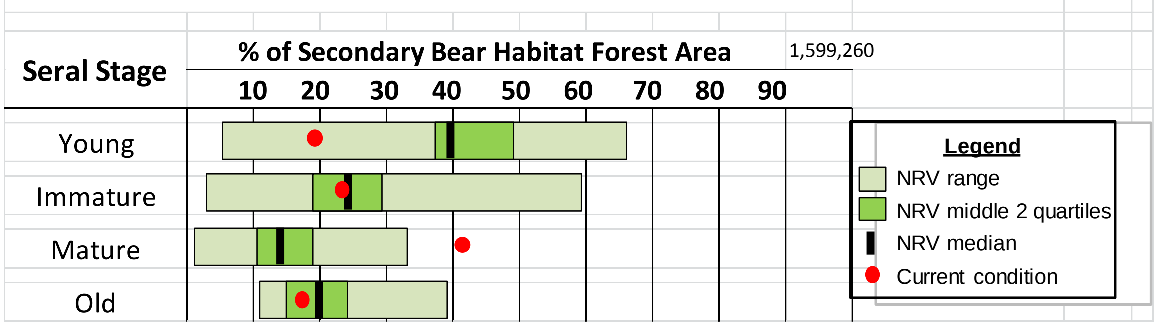


6.1.7 Passive vs. Active Land Base

Most forest management agencies in Canada must identify those parts of the forested area within an FMA area that is eligible to be harvested versus those that are not. In Alberta, these are known as the *active* and *passive* land bases respectively. For this study, the active-passive maps were obtained from the two largest FMA holders in the study area (i.e., Canfor and Weyerhaeuser).

6.1.7.1 Canfor FMA Area

Figure 29. Historical Range of Secondary Grizzly Bear Habitat in the Upper Peace



Note that the NRV patterns for the two forest types were similar but not identical (Figures 30 and 31). This is relevant because neither one represented a single fuel-type, but rather a combination of several different types — representing a number of different unique fire regimes.

The difference in current conditions between the two areas was far more significant. Active young forest on the Canfor FMA area currently sits at 19% (Figure 30), compared to just 8% for the passive land base (Figure 31). Similarly, immature young forest currently accounts for 30%, double the 15% of immature forest in the passive areas. However, the 35% of mature forest in the active land base was significantly lower than the 43% currently in the passive land base, and the 16% of old forest currently in the old seral-stage in the active land base was more than twice the amount of passive old forest (Figures 30 and 31). The fact that the deviations between the two types of forest were so large for both the young and immature seral-stages suggests that disturbance levels have been consistently and significantly lower in the passive forest areas for many decades.

Figure 30. Historical Range of the Active Land Base on the Alberta Canfor FMA Area

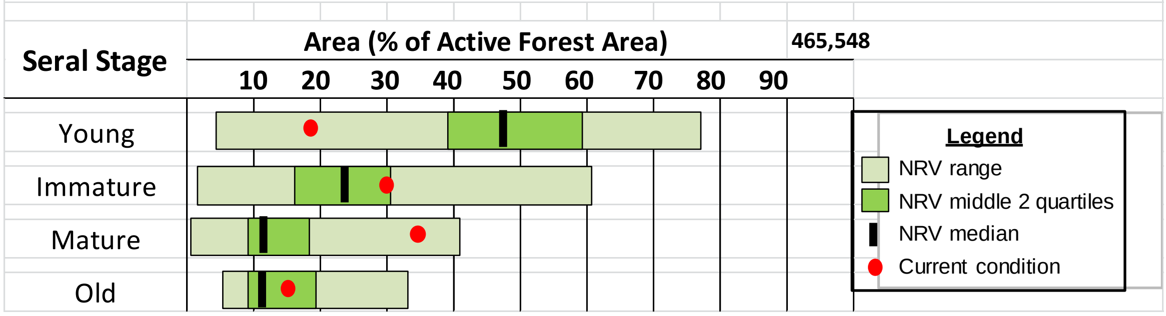
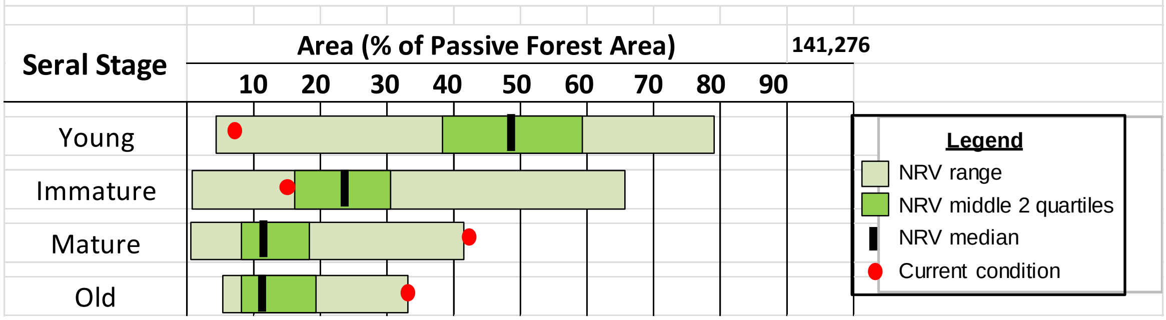


Figure 31. Historical Range of the Passive Land Base of the Alberta Canfor FMA Area



6.1.7.2 Weyerhaeuser FMA Area (Grande Prairie)

The differences between active and passive for the Weyerhaeuser (GP) FMA area were mostly, but not entirely similar to those from the Canfor FMA area. Mature and old forest increased from 38% and 20% to 44% and 28% respectively between the active and passive forest areas. Similarly, young forest dropped from 20% to 7% from active to passive. However, the amount of immature forest was virtually identical between active and passive (Figures 32 and 33 respectively). This suggests that either harvesting levels on the Weyerhaeuser FMA were much lower 40–80 years ago, or there was far more wildfire activity on the Canfor FMA area 40–80 years ago.

Figure 32. Historical Range for the Active Land Base of the Weyerhaeuser Grande Prairie FMA

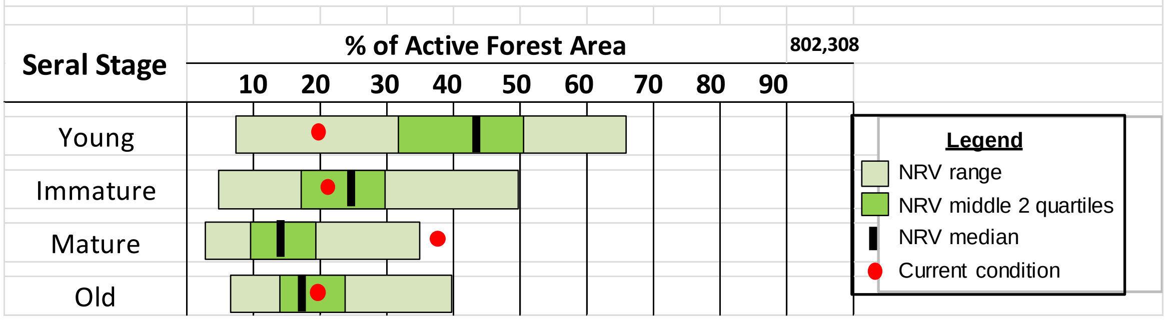
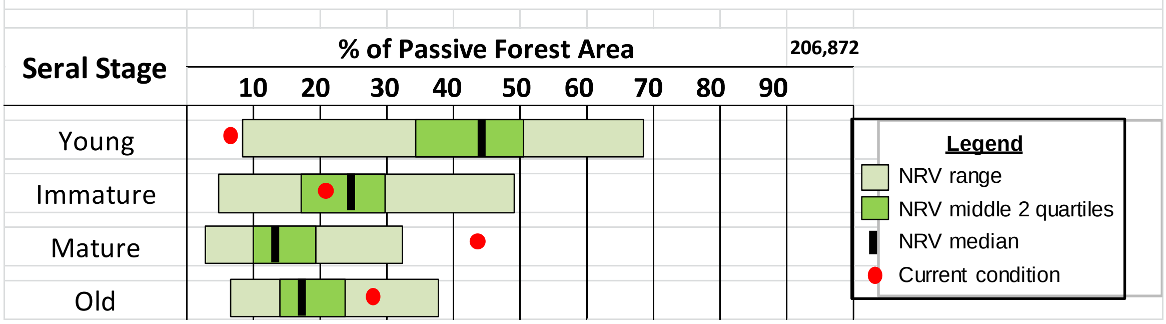


Figure 33. Historical Range for the Passive Land Base of the Weyerhaeuser Grande Prairie FMA

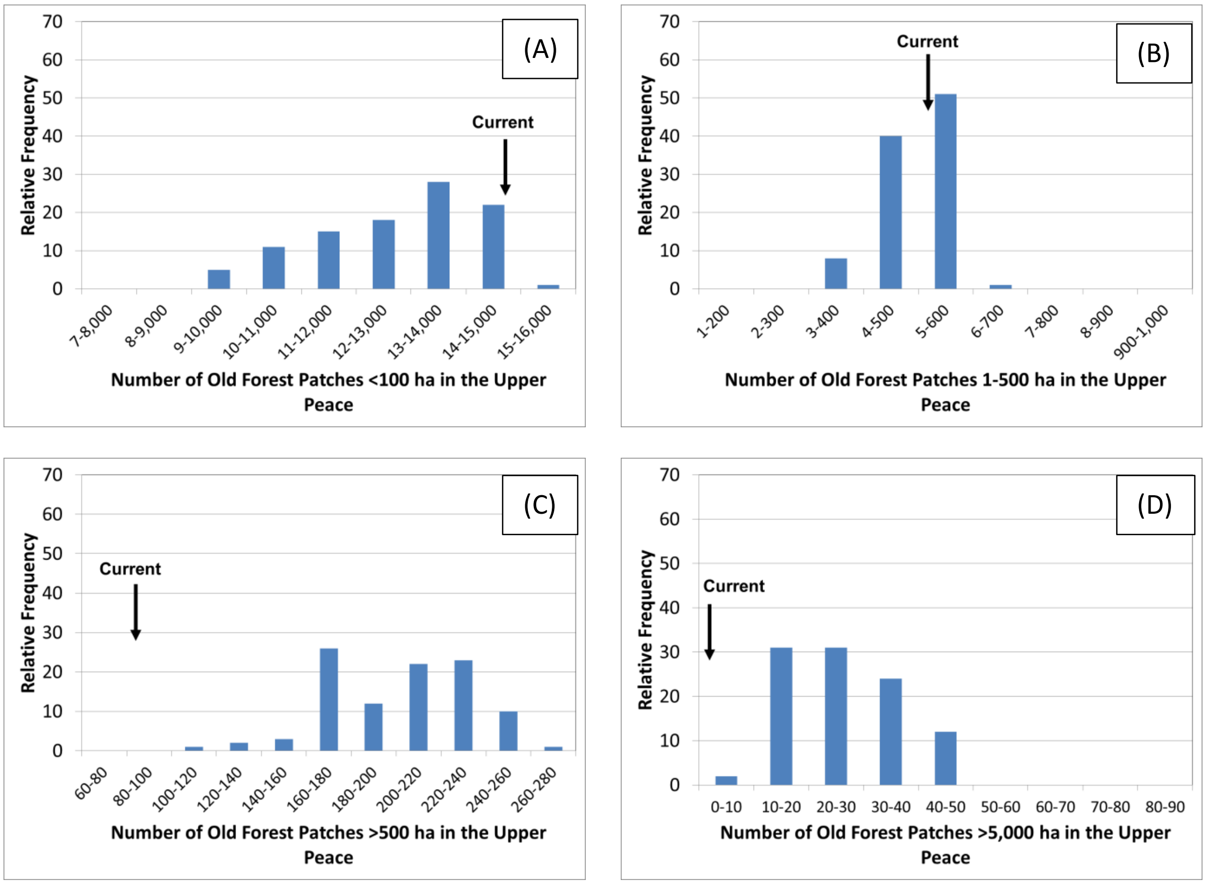


6.2 Spatial Results

Results are presented here for four patch sizes of old forest: <100 ha, 100–500 ha, >500 ha, and >5000 ha. A ***patch*** was in this case defined by that portion of an otherwise contiguous age polygon that lies *only* within the boundaries of the study area. Large forest patches that extend beyond the boundaries of the study area were captured by the model, but not reported. The current condition was calculated using any and all available linear and polygon feature data available at the time.

The number of small (i.e., <100 ha) old forest patches on the study area today (14 692) was on the high end of that generated by the NRV modelling exercise (9182–15 292) (Figure 34A). The 511 old forest patches currently observed between 1 and 500 ha was close to the median of 373–603 patches historically (Figure 34b). Old forest patches larger than 500 ha range from 116–261 historically, compared to only 82 currently observed (Figure 34C). And finally, the NRV of old forest patches >5000 ha ranged from 8–47, compared to just two currently observed (Figure 34D). In other words, old forest patches larger than 500 ha are well below that expected historically on the Upper Peace landscape.

Figure 34. NRV (blue bars) and current condition (black arrow) of old forest patch sizes on the Upper Peace area. Upper left (A) is all old forest patches <100 ha. Upper right (B) is all old forest patches 1–500 ha. Lower left (C) is all old forest patches >500 ha. Lower right (D) is all old forest patches >5000 ha.



7.0 Discussion

7.1 Overall Results

Spatial modelling exercises such as this generate a large amount of output. While this is an extraordinary opportunity to be able to explore pre-industrial landscape patterns in detail, it also presents a challenge to identify the most relevant signals. Addressing this challenge, the results in this study tell a single, consistent story: ***disturbance rates have been low for several decades, which have created very low levels of young forest, and high level of mature and in some cases old forest today relative to historical conditions***.

The overall current level of old forest in the Upper Peace is actually well within NRV, and creates a modest buffer against inevitable natural disturbance events such as wildfire and insect outbreaks. Thus, *considered in isolation*, this seems a reasonable outcome. However, this is not true for all old forest types. This study suggests that old forest levels in black spruce and white spruce forest areas, as well as in passive forest areas, are already beyond NRV.

Of greater concern is the fact that the current level of mature forest is consistently and well beyond the upper threshold of NRV for the entire study area. Consider that, barring significant increases in disturbance levels, the data suggest that the majority of mature forest will shift to old forest in the next 10–20 years. In other words, this landscape is now, and will likely remain unbalanced for the foreseeable future relative to historical conditions. These findings are consistent with those found in previous NRV spatial modelling exercises in the western boreal including Sundre Forest Products, Hinton Wood Products, Alberta Newsprint Company, Canfor, Tolko, Alberta Pacific, and Mistik Management.

The amount of area that will shift from mature to old forest from this point forward depends on a) how much disturbance will take place, and b) where and how disturbance will take place. For the sake of argument, we can start with a business-as-usual (BAU) scenario in which policies and practices do not change and look forward another 20 years. Recall that the 12% of young forest (<40 years of age) represents the 1st percentile of NRV. For context, the NRV median was more than four times higher at 45%. If we use the disturbance levels of the last 40 years as a benchmark for the future, we know that an average of 0.3% (12%/40 years) of the landscape has been disturbed each year over at least the last 40 years. So, under this disturbance scenario, in another 20 years, that will convert 6% (20 × 0.3) of mature and old forest to the young seral stage. Even under this idealistic scenario (i.e., not including any harvesting restrictions in caribou zones), once the shift from young to immature, immature to mature, and mature to old are taken into account over the next 20 years, the amount of old + mature forest will be much further beyond NRV than it is now.

Admittedly, the above simplistic scenario is not very realistic. For example, climate change predictions suggest that it is likely that wildfires will become more common, and more severe in the future despite our best control efforts (Flannigan et al. 2000). This will both increase the overall level of disturbance, as well as negate the assumption that disturbance will only occur in mature and old seral-stages. A simple non-spatial mathematical exercise confirms that even if future wildfire + harvesting levels on this landscape are quadruple that of the last 40 years, the amount of old + mature forest will still be beyond NRV 20 years from now. However, under this scenario one must also account for the potential catastrophic social and economic cost of increased wildfire activity that may reduce the gap between NRV and current condition. So, if anything, a more realistic future scenario for this landscape poses far greater challenges and risks than the simplistic one outlined above.

It is interesting to consider the spatial and non-spatial results together. Under natural conditions, as the amount of old forest increases, the probability of finding larger patches of old forest should increase. Based on that logic, one would expect the number of old forest patches today to be near the median of NRV. In reality, the current number of larger old forest patches was below the lower end of NRV. The results also suggest that the chances of having very large patches (at least 5000 ha) is far less likely than that of having merely large patches (at least 500 ha).

There are several possible reasons for this discrepancy. One possibility is the nature of *all* anthropogenic disturbance patterns over time and space over the past several decades. We know that anthropogenic disturbances on this landscape take one of four main forms:

1) Settlement (e.g., roads, towns, land conversion, and various rights of way),
2) Forest harvesting activities (harvesting plus roads),
3) Activities from the energy sector (e.g., roads, seismic lines, well sites, and other infrastructure), and
4) Other industry (e.g., borrow pits, surface mining).

Research suggests that the impacts of the energy sector on landscape patterns far outweigh those of forestry in Alberta, despite the fact that the physical footprint of the energy sector is much smaller (Pickell et al. 2013). Moreover, historical provincial harvesting regulations mandated multi-pass "checkerboard" patterns for several decades, which tended to artificially spread out disturbance patterns spatially creating less opportunity for large old forest patches (Pickell et al. 2015). In the end, the only way of understanding the impact of each of these factors on old forest patch size is to conduct a more comprehensive spatial analysis than this study was intended to provide.

7.2 The Details

The specifics of how NRV compares to current condition for the Upper Peace landscape are highly informative. For example, the results between the ***active*** and ***passive*** forest types were unexpected in two ways. First, the degree to which the passive (i.e., un-harvestable) part of the landscape was already beyond NRV was surprising. The amount of passive forest older than 40–80 years was well beyond NRV suggesting decades-long fire control policies and practices have been extremely successful. ***The only way to that the passive part of the landscape could shift back into NRV over the next 10+ years is if the disturbance rate on the passive land base increased <u>at least eight-fold,</u> relative to that of the last several decades.*** Since these areas are currently not economically viable for the forest industry, this means either allowing more wildfires to burn under controlled conditions, more wildfires will burn under uncontrolled conditions, more prescribed fires, introducing alternative forest product streams for passive forest areas (e.g., pellets), or non-commercial mechanical disturbance. Otherwise, the gap between current and historical conditions will only continue to widen in the passive land base area.

The second surprise was that even on the so-called ***active*** portion of the land base, old and mature forest levels were still relatively high, and young forest levels were relatively low. One of the long-held tenets of forest management in Canada is the concept of sustained yield, which proposes an annual harvest volume equivalent to the annual growth of the forest. The large amount of mature and older forest on the active land base could be due to 1) lower than planned for harvest levels, 2) harvesting restrictions based on fine-filter requirements (e.g., caribou range areas) or 3) higher LTFC assumptions than used in this study. The low level of young active forest suggests that harvesting levels have for several decades been much lower than the average disturbance levels that occurred historically.

The details of NRV and current condition for the caribou ranges in the study area were also highly informative. The current levels of "recovered" forest (>40 years of age) were well within the Environment Canada (2012) requirements for all five ranges in the study area. In reality, the Environment Canada requirements were only met 31–71% of the time historically by the NRV modelling exercise. In other words, in the pre-industrial era, woodland caribou did not exist in the five current caribou ranges in the study area 29–69% of the time. These results suggest one of three explanations;

a) One or more habitat modelling assumptions or methods were tragically in error (see next Section)
b) Woodland caribou historically moved around to alternative suitable habitat in response to wildfire disturbances, or
c) The assumption that any forest area disturbed from a wildfire less than 40 years of age is unsuitable habitat for caribou *is tragically in error*.

The actual explanation may be a combination of all three. Option (a) is explored in more detail below. Further exploration of options (b) and (c) are beyond the scope of this study, but may be the keys to future caribou survival efforts.

7.3 Possible Sources of Error in the Model

One of the most widely paraphrased quotes about modelling is from George Box (1979): *all models are wrong, but some are useful*[1]. What he meant by this is, a) models are only representations of reality, b) every model (should) has a very specific purpose, and c) precise models are not necessarily "better" than accurate ones (Hammah and Curran 2009). This leads nicely to the concept of parsimony: The best models should have the minimum number of parameters and assumptions necessary to address the objectives and explain the phenomenon, but no more (Haag and Kaupenjohann 2001). In other words, what is the bare minimum number of pieces moving parts to achieve the modelling goal? Parsimony also suggests that not all those parts or pieces influence the output equally.

Keeping in mind both Box's advice, and the concept of parsimony, recall that the purpose of this particular modelling exercise was to define some broad and simple landscape-scale pre-industrial pattern metrics. Thus, the question is not whether the model simulated fire pattern, probability of vegetative sprouting, or the inclusion/exclusion of specific fire behaviour patterns in the model are "right", but rather which factors, parameters, or assumptions are mostly likely to *significantly* alter the desired output. Thanks to the simplicity of the model — and its purpose — the possibilities are limited.

The most significant factor driving the *area of different seral-stages* (i.e., all of Section 6.1) is the frequency of disturbance. To illustrate, using a simple negative exponential mathematical model that is broadly associated with representing age-class distributions in the boreal forest (Johnson 1992), the average amount of forest older than 120 years with a 65 year long-term fire cycle (LTFC) is 16%,

[1] The idea originally presented in: Box, G. E. P. 1976. Science and Statistics. Journal of the American Statistical Association 71:791–799.

compared to 20% for a LTFC of 75 years, and 26% for a landscape with a LTFC of 90 years. The process for identifying pre-industrial LTFCs in the study area was through and extensive, including a) an informal review of historical local records, b) a literature review, c) a two-day expert workshop, and d) four iterations of a LTFC map from anonymous expert opinion over four years (see Andison 2019a). It should be noted that this modelling was done prior to the completion of the final LTFC map produced from the iterative exercise. However, as discussed earlier, the most important LTFC numbers used for this project were unaffected.

In the end, the LTFC map from Andison (2019) clearly represents the *best available science*, given the breadth and depth of effort. Having said that, one of the advantages of a spatial modelling exercise is the ability to test input assumptions (including LTFCs) via a sensitivity analysis. Aptly named, a sensitivity analysis allows one to test the effect of changing the input assumptions on model output, which in this case would be the LTFC numbers.

Another possible source of significant error could be the under-representation of low and moderate severity fires in the model. As with every other landscape-scale model today, Landmine captures and represents severity in a simplistic, binary fashion: In other words, either a pixel burns, or it does not. However, evidence suggests that some percentage of historical fires left behind significant areas of partially burned forest (Andison 2004).

Although the inclusion of low to moderate severity fires in a spatial model is likely important, their influence on the output of this project is unclear. The first issue is the potential lack of documentation of such fires. Smaller, lower intensity fires could easily be missed by historical mapping methods. The result is that the historical LTFCs may actually be *higher* than empirical data suggest in order to capture lower intensity fires (e.g., Amoroso et al. 2011). A second, related issue is if, or how, we define a seral-stage. The boreal has for decades been considered to be a stand-replacing ecosystem (Johnson 1992) that can be represented spatially by the date of the last disturbance. The introduction of low to moderate severity fires challenges, and suggests expanding on, these simpler definitions to capture more complex forest age structures. In the end, there is no evidence to suggest how, or in which direction, the inclusion of low and moderate severity fires might impact the output from this study. Moreover, there currently exists no spatial model that accounts for partial mortality.

The last potential source of error in the model output is that the current condition estimates — both spatial and non-spatial. With respect to current condition for the non-spatial results (i.e., the red dots), ages are taken from the most recent forest inventory. While AVI captures age data for every forest polygon, identifying the exact stand age is not a high priority for forest inventories. Comparisons suggest that accuracy is more of a concern than bias (Andison 1999a, 1999b). Moreover, inventory age estimates of older stands decrease in accuracy, and increase in bias (Andison 1999a, 1999b). It may also be true that the current condition data provided at the time of this study are now outdated, and could be replaced.

There are two challenges regarding the calculation of current condition for patch sizes. The first is tracking, classifying, and dating each disturbance feature. As with age data, AVI does not prioritize capturing details on all types of these data as part of its primary purpose. Fortunately, other agencies (e.g., the Alberta Biodiversity Monitoring Institute (ABMI)) have more recently been making significant progress on a province wide database of disturbance features that could be used to re-calculate the current conditions for this project.

The second challenge of the current condition estimate for patch sizes is more daunting; how does one integrate and compare the impacts of forest edges from different sources and vintages? For example, if/how do we differentiate edges associated with highways from that from a bush road, from that from a large, new seismic line, from that of a small and/or very old seismic line? For this study, any and all disturbance features were used, but this could easily be augmented by a sensitivity analysis that creates 4–6 different “edge” scenarios, perhaps using new ABMI data.

7.4 Implications

In theory, a landscape that has moved / is moving beyond NRV potentially creates greater risks to the sustainable flow of goods and services, and is less resilient to the impacts of future perturbations (Christensen et al. 1996, Hunter 1996). One of the more obvious risks is the increased threat of natural disturbance. Towards that, the current level of forest >80 years of age is more than double that of the average historical level, which means a higher than average amount of dense, continuous fuel that is more susceptible to wildfire, insect, and disease. We are already seeing some of the potential social, economic, and ecological costs of this fuel buildup in other parts of western Canada and beyond in the form of large wildfires that threaten communities and infrastructure, and the unprecedented eastward spread of the mountain pine beetle. As the large amount of mature forests shifts to old forest on this landscape in concert with climate change, these risks will only increase. Note that this risk also translates into a lower probability that existing woodland caribou ranges will survive intact over the short term.

Perhaps less obvious, but just as important is the risk associated with significant loss of and/or changes to habitat types. To demonstrate, Table 6 shows the current area in each of the four seral-stages for each of the five major forest types — a combination often used to represent generic *ecotypes*. The four colour codes denote where each lies today within the associated NRV ranges: the middle two quartiles

Table 6. Summary of the area modelled in this project, showing how the current level of forest relates to NRV.

Seral-Stage	Species Type				
	Pine	Sw	Sb	Aw	Mix
Young	227,050	68,543	29,181	235,090	107,428
Immature	174,501	87,876	204,978	904,405	157,327
Mature	427,330	193,327	280,421	1,554,359	249,492
Old	162,603	236,094	197,149	71,910	72,206

Legend
Middle two quartiles
Within 95% CI of NRV
Betweem 95-100% CI of NRV
Beyond NRV

(dark green), the 95th percentile (any green), beyond the 95th confidence interval (light red), or beyond NRV (dark red) (Table 6). For context, each and every NRV landscape snapshot generated from the modelling exercise would be (light or dark) green for all 32 cells.

The visual patterns from Table 6 alone are telling. Of the 20 different ecotypes, the current conditions of 11 (or 55%) are green. The current conditions of another seven ecotypes (or 35%) are already beyond NRV (i.e., dark red). But those seven ecotypes account for more than half of the forest. Of even greater concern is the fact that in the absence of significant changes to forest land management policy and/or practice, more ecotypes on the study area will move beyond NRV in the near future (Table 6).

From an ecological perspective, Table 6 represents a fundamental imbalance of landscape scale diversity. Biodiversity is widely recognized as being partitioned into two parts; 1) Richness (the absolute number of ecological elements), and 2) Evenness (the relative proportion of each element (DeJong 1975)). In this case, the number of elements (i.e., richness) has not changed relative to NRV, but the current proportion (i.e., evenness) of each has, and in some cases dramatically so. At landscape scales, species and ecosystem functions have evolved over thousands of years, relying on a natural range of ecotype proportions over time and space. EBM theory suggests that pushing a landscape system beyond this natural range is likely to create some unexpected and very likely negative outcomes for the resident species and services (Pickett et al. 1992). For example, as discussed above, a large amount of older forest will create a higher risk to wildfire, insects, and disease. This demonstrates the risks of *over-represented* ecotypes on a landscape.

A less obvious, but perhaps equally important risk is *under-represented* ecotypes. While we tend to associate this particular risk with old forest habitat, in this case the risk is actually a loss of young forest habitat. For example, young black spruce stands averaged about 313 000 ha historically in the study area, compared to just over 29 000 ha today. The under-representation of one or more ecotypes across a large landscape should be cause for concern — including young forest. Although not widely discussed, the unique and critical habitat conditions, environmental conditions, and soil nutrient profiles necessary for the foundation and existence of a large number of boreal species habitat conditions produced by disturbance create a biological peak in diversity 1–5 years after wildfire (Coop et al. 2010, Yeager et al. 2005). Designing future landscapes that include levels of young forest below those experienced historically is likely to negatively impact the health, integrity, and resilience of the landscape ecosystem.

The potential implications of a shortage of large old forest patches identified in this study are more straightforward. Similar to the logic from above for ecotype distribution, there are a range of species that favour forest edge and those that favour forest interior (Magura 2002). We also know that the amount of forest edge currently in the study area exceeds anything ever experienced historically, which is why there are very few large old forest patches relative to NRV. Unless the interior forest dependent species are able to adapt, it is reasonable to presume that the population levels of such species will decline. The decline of contiguous old forest patches in the boreal is neither a new pattern, nor a surprising one (i.e., Pickell et al 2016).

What is less well understood are the specifics of a) what constitutes an edge, and b) what defines a patch (and for whom or what)? As discussed above, the measurement of current condition used in this study was a simple GIS exercise based on all existing available spatial layers, including forest inventory, roads, water features, and seismic lines. The calculation did not differentiate among edges generated from a highway or a bush road or from that of a large new seismic line or even that from an old narrow seismic line. An otherwise contiguous old forest patch size assessment in this study was likely biased by treating all forms of edge creation as equal. It is not difficult to imagine different species responding differently to each edge forms. Although this project was not intended to address these many and important questions, the answers are highly relevant.

Notwithstanding these many questions, this project does offer one of the first spatial analyses of landscape patterns for the study area. Thus, the results offer a starting point for not only compliance discussions with key coarse-filter indicators, but also a foundation for methodologically, and ecologically discussions of relevance.

7.5 The Future of This Landscape

It is important to emphasize that the results from this project do not just tell the story of how the current landscape compares to historical ones at one point in time and space, but also the direction of travel for this landscape. Projecting the study area seral-stage patterns forward in time over several decades suggests that current policies and practices will only take this landscape further beyond NRV in the not too distant future. Existing requirements that limit disturbance in caribou zones will only magnify this trend. In other words, the most likely scenario is that in 20 years Table 6 will be mostly red. From an ecosystem-based management (EBM) perspective, this is not just an unbalanced landscape, but one that is ultimately headed in the wrong direction in terms of resilience and sustainability in the absence of significant changes to policies and practices as regards how we manage all forms of disturbance activities. Lastly, given the massive amount of forest in the 80–110 year range in the study area today, the longer we avoid making changes to policies and practices, the more difficult, risky, and costly it will be to reverse this trend.

7.6 New Questions

The ultimate measure of a research project is the number and quality of new questions that it creates. This study generated no shortage of new questions:

1) **Do we fully understand the ecological (and associated social and economic) implications of under-represented ecotypes?** The most obvious knowledge gap here is the ecological (and by association economic and social) value of disturbance in non-forested areas, including wetlands, but more generally the so-named “passive” landscape. Although it may be well recognized that wetlands provide significant ecological benefits to the boreal ecosystem, we have very little understanding of those details, particularly as it relates to wildfire.
2) **What are the potential (new, increased, decreased) risks of staying the course with respect to policies and practices?** It is not difficult to project what this landscape will look like 20 years in

the future in terms of disturbance planning under business as usual (BAU) policies and practices — relative to NRV. The forest will continue to age, the risk of natural disturbance threat will increase, the negative social, ecological, and economic implications will only increase, and the chances of maintaining critical habitat for woodland caribou will decline. What we are less clear on is what future landscapes might look like under alternative policy/practice assumptions. Spatial modelling technology allows us to explore such alternatives, and it would be a worthy extension of this project.

3) **What is the potential for forest management and fire management to work together?** One could argue that the key to the future for boreal sustainability is a collaboration between forest and fire management. In the short term, steps to improve cooperation between these two otherwise independent government agencies can only be a positive contribution to addressing many of the regulatory and management challenges discussed in this study. This could / should include pilot studies, high-level policy discussions, and demonstrations.
4) **What is the ecological impact of defining "patches" in different ways?** How a patch is defined, and by what linear or polygon features, will no doubt be different for different species and values. More specifically, for this study, it would be useful to (re)calculate the current condition of old forest patch size based on a range of assumptions. This simple GIS calculation is likely to reveal critical information in terms of sources and degree of anthropogenic impact. In the bigger picture, initiating technical standards through collaborative discussions with all stakeholders would be wise.
5) **(How) Will climate change modify the nature of any of the challenges noted above?** Recall that all of the results and discussions captured here were based on historical fire activity, which is intimately linked to historical climate patterns. The fact that future climate is likely to be different does not invalidate these results. Rather, understanding past climate conditions and fire activity is a necessity in preparation for the consequences of climate change on fire regimes, regardless of whether the past represents the future.

8.0 RECOMMENDATIONS

The following are the opinions of the author, and do not necessarily reflect the opinions of either fRI Research or the Healthy Landscapes Activity team.

1) **Use the results from this study as an early warning system for ecosystem health concerns.** Landscape patterns have momentum that can take several years or even decades to shift beyond their historical range. The responses of the resident species to such departures may take even longer to be observable. As a result, the implications of policies and practices based on fine-filter values are often only obvious many years or decades later. In other words, value-based management systems force us to continually be responding to known, existing threats. Shifting to a more pro-active management paradigm lies at the heart of an NRV strategy.

Notwithstanding climate change implications, in the absence of a perfect understanding of how ecosystems function, an NRV strategy assumes that the historical range of patterns is a relatively safe range within which to manage that minimizes the degradation of ecosystem function and resilience while providing for a sustainable flow of goods and services. In other words, an NRV strategy is the ultimate manifestation of the precautionary principle. For example, when we first notice landscapes deviating from pre-industrial (NRV) patterns, that is a critical red flag — and one that is observable far ahead of the associated fine-filter red flags. We can be more proactive by paying attention to coarse-filter red flags. This project has identified several such critical NRV red flags (e.g., scarcity of young black spruce forest type).

2) **Change the channel on the role / importance of disturbance**. For too long, disturbance has been associated with mostly negative social, economic, and ecological consequences. From an ecological perspective the boreal is now, and always will be, a disturbance-dependent ecosystem. This means one of the ultimate measures of a healthy ecosystem (and thus sustainability, social and economic values) is the *quality* of disturbance activities, not the *existence* of them. Within and beyond Canada this message is becoming more common, but all forest land management agencies should be highlighting the necessary and positive role of disturbance — *of the appropriate quality*.

3) **Move towards co-management**. The challenges of adopting an NRV strategy through the information in this report are far from trivial, and are beyond that which any single agency (private, government, Indigenous Peoples, forestry, fire, etc.) can or should attempt to manage on their own. Assuming all parties agree that the results of this project are concerning (as per the red flags in point #1), this creates a foundation for working together across both jurisdictional boundaries and agency-specific objectives.

4) **Support proactive research**. Natural resource research priorities tend to shift over time, often in response to the degree to which species or values get negative attention. We should, and now have the ability to get ahead of that curve by understanding and anticipating funding future challenges as per the argument in point #1. The five questions posed in the previous Section (7.5) are an excellent starting point.

5) **Share, listen, and be humble**. This project generated a large amount of new and valuable information. The results can and should be a part of the next generation of planning. However, the results also challenge what we believe about old forest, resilience, sustainability, and even value-based management approaches. Thus, the results, and their potential implications (including these recommendations!), should also be part of any future stakeholder dialogue.

6) **Accept and present the results in this report as the best available evidence.** The output from this project represents a rigorous, innovative, and well-documented process from a multi-disciplinary team over several years in terms of model design, model assumptions, and spatial data. In other words, the results represent the best available science. There will always be arguments for further / better evidence, and no doubt the results from this project will be

superseded in 5–10 years. However, this is the nature of how knowledge grows, and should never be used as an excuse to avoid making policy and practice decisions today.

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