


FINAL REPORT

Understanding Historical Landscape Patterns on the Weyerhaeuser Grande Prairie FMA Area in Alberta

Final Report

fRI Research Healthy Landscapes Program

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Any opinions expressed in this report are those of the authors, and do not necessarily reflect those of the organizations for which they work, or fRI Research.

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CONTENTS

Disclaimer ... 1
Acknowledgements ... 2
Executive Summary ... 4
1.0 Introduction ... 5
2.0 Goal ... 5
3.0 Background ... 6
3.1 LandWeb ... 6
4.0 Study Area ... 7
5.0 Methods ... 9
5.1 Creating Pre-Industrial Landscapes ... 9
5.1.1 Model Assumptions ... 9
5.2 Spatial Data ... 10
5.2.1 Pre-industrial Vegetation ... 10
5.2.2 Current Condition ... 11
5.3 Model Calibration ... 12
5.3.1 Fire Frequency ... 12
5.3.2 Fire Size ... 14
5.3.3 Fire Severity ... 14
5.4 Running Landmine ... 15
6.0 Results ... 15
6.1 Non-spatial Results ... 15
6.1.1 Weyerhaeuser Overall ... 16
6.1.2 Weyerhaeuser FMA Areas ... 17
6.1.3 Major Vegetation Types ... 17
6.1.4 Ecological Natural Subregions ... 21
6.1.5 Woodland Caribou Ranges ... 23
6.1.6 Grizzly Bear Habitat ... 24
6.1.7 Passive vs. Active Land base ... 25
6.2 Spatial Results ... 26
6.2.1 Weyerhaeuser FMA Area ... 27
6.2.2 The Saddle Hills Management Area ... 28
6.2.3 The South Management Area ... 29
7.0 Discussion ... 30
7.1 Overall Results ... 30
7.2 The Details ... 31
7.3 Possible Sources of Error in the Model ... 32
7.4 Implications ... 34
7.5 The Future of This Landscape ... 36
7.6 New Questions ... 37
8.0 Recommendations ... 38
Literature Cited ... 40

Executive Summary

This project was a spatial modelling exercise that created coarse-scale pre-industrial landscape metrics of the Weyerhaeuser Grande Prairie FMA area in Alberta. The primary goal was to understand if, or in what ways the current condition of the FMA area align with the historical "*natural*" range. The results suggest that much of this landscape is statistically well beyond its historical range. More specifically, the amount of mature (80–120 years) and old (>120 years) is in many cases currently very close to or beyond the upper natural range of variation (NRV) threshold. On the other hand, the overall amount of young (<40 years) forest was close to or beyond the lower NRV threshold for the landscape. 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 and black spruce dominated areas. This suggests that wildfire control efforts have been effective for several decades. However, even the so-called "active" landbase shows this deviation pattern from NRV suggesting that historical harvesting levels have been lower than historical disturbance rates for several decades.

A large amount of old forest can provide positive benefits to a landscape in the form of a buffer against natural disturbance and critical habitat. On the other hand, holding old forest levels beyond NRV increases the risk of natural disturbances such as wildfires or insect and disease outbreaks. This study also revealed that many of the ecological benefits of older forest on the Saddle Hills part of this landscape have been compromised by anthropogenic disturbance patterns that dissect what would otherwise be large contiguous patches of old forest into smaller patches. The larger, South FMA area currently has large patches of old forest consistent with NRV data, although this project represents the first of what should be several phases of evaluating spatial patterns.

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 to widen.

Overall, the metrics from this study suggest that this is an unbalanced landscape that is headed 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 and McCleary 2014). This means that historical levels of old forest are likely to be both highly dynamic and spatially variable as well.

In the absence of detailed and multiple historical data and/or photos, the only means left to capture 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 (observed, 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 in a number of ways to capture the desired metrics, and then summarized to generate NRV.

This report summarizes the results of a spatial modelling exercise designed to generate NRV summaries for the Weyerhaeuser Company Grande Prairie forest management agreement (FMA) area in 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 Weyerhaeuser Grande Prairie FMA area in Alberta relative to the current condition***. Note that this goal is both narrow (it will capture only landscape scale patterns) and humble (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 roughly to the 62nd parallel into the NWT. The area includes 73 million ha of the Boreal Plain, 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) (Fig 1).

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

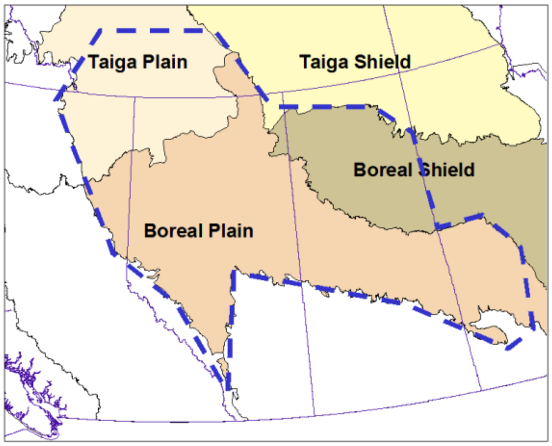
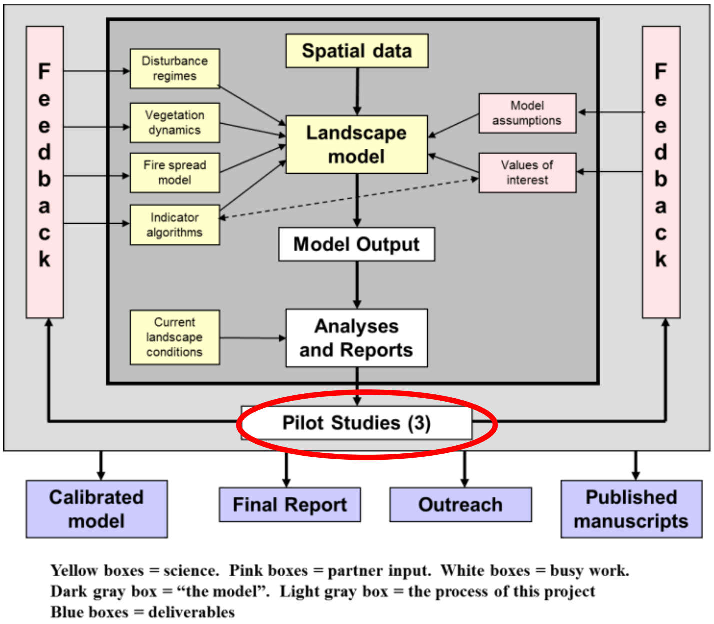


Figure 2. Overview of LandWeb Project Elements.



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*.

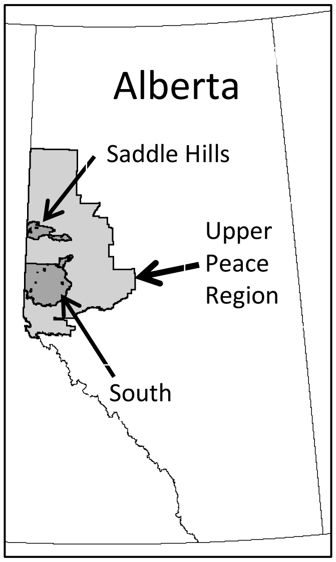
As one (of potentially dozens of possible) configuration of SpaDES, it was recognized that multiple iterations of LandWeb would likely be developed over time, each one adding layers of sophistication, ease of use, or robustness as the case may be. However, the original vision of the very first version of LandWeb was very 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 can be built and run. In support of this vision, that 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) developing and testing techniques for dealing with the complexities of multiple regime zones in a spatial model.

4.0 Study Area

The area modelled as part of this pilot study was the entire greater Upper Peace (land use framework) region of Alberta, covering over almost 7.5 million hectares. However, the summaries provided in this report are limited to the two distinct areas of the Weyerhaeuser Grande Prairie FMA totalling almost 1,118,000 ha; the Saddle Hills area (211,000 ha), and the South area (907,000 ha) (Figure 3). The modelling results for the greater modelling area will be available through fRI Research in the next few months.

Figure 3. Study area map showing the Weyerhaeuser Grande Prairie FMA.



Of the total area in the Weyerhaeuser FMA, almost 108,000 ha, or 10% is non-forested. Another 30% (almost 338,000 ha) is deciduous leading, 24% pine leading (267,000 ha), 17% of white spruce leading, 12% mixedwood leading, and 12% black spruce leading (Table 1).

Table 1. Summary of Weyerhaeuser Grande Prairie FMA area by leading species type.

Leading Species	Area	
	Hectares	%
Pine	266,532	24
White Spruce	186,316	17
Black Spruce	82,220	7
Deciduous	337,616	30
Mixedwood	137,432	12
Total forested	1,010,160	90
Non-forested	107,619	10
TOTAL	**1,117,779**	**100**

Ecologically, the Weyerhaeuser FMA is quite diverse. Almost half (48%) of the FMA is represented by the lower foothills natural subregion (NSR), followed by the upper foothills (22%), subalpine (13%) and the central mixedwood (12%) (Table 2). The relatively small proportions of dry mixedwood (4%), and montane (1%) NSRs are all ecotonal (i.e., mostly within close proximity to the other major NSRs)

Table 2. Summary of Weyerhaeuser FMA area by Natural Subregions (NSR)

NSR Name	Area	
	hectares	%
Alpine	40	0
Central Mixedwood	132,088	12
Dry Mixedwood	49,788	4
Lower Foothills	535,810	48
Montane	7,283	1
Subalpine	143,355	13
Upper Foothills	249,415	22
TOTAL	**1,117,779**	**100**

The details of the range of ecological conditions on the Weyerhaeuser FMA are noteworthy and highly relevant to the NRV modelling and output. It spans an elevation from 200 to >1500 m, growing degree days from 800–1250, mean annual precipitation from 500–760mm, and from level to steeply sloped topography (Table 3). In other words, this is by no means a homogenous study area in terms of either biotic or abiotic elements. Nor is it homogeneous in terms of historic (or future) fire behaviour or risk. For example, estimates of the pre-historic long-term fire cycle averages for the different sub-regions in the Weyerhaeuser FMA range from 65–135 years (Andison 2019a) (see ahead to Figure 4). Furthermore, there is a strong alignment between the long-term fire frequency estimates, and many critical wildfire elements. For example, longer fire cycles are associated with low elevation (i.e., higher lighting ignition probability), longer growing (and fire) seasons, and more flammable fuel types.

Table 3. Summary of the biotic and abiotic conditions across the Weyerhaeuser Grande Prairie FMA.

Natural Region	Natural Subregion	Elevation	Topography	Climate	Vegetation	Soils	Growing Degree Days >5^{0}C	Mean annual Precip (mm)	Relative Summer Moisture Index
Rocky Mountain	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
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	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
Boreal Forest	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

5.0 Methods

As previously (Section 4.0) discussed, the modelling described in this section was actually based on the entire Upper Peace region of Alberta. Thus, most (but not all) of the methods are the same, but the results (for Weyerhaeuser) are unique.

5.1 Creating Pre-Industrial Landscapes

At the heart of any attempt to generate pre-industrial landscape conditions is the formulation and assumptions 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 possible past 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 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 — usually 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 historical area burnt (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. The rule of thumb 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, as defined by Weyerhaeuser:

- By the two separate FMA areas (South and Saddle Hills),
- By the provincial natural subregions (NSRs),
- By the major forest cover-types,
- By woodland caribou range boundaries, and
- By primary and secondary grizzly bear zones.

The project also includes defining the NRV for the (spatial) sizes of old forest patches for:

- All old forest combined, and "Old" forest as defined by each of the major forest types for five patch sizes: 1) <50 ha, 2) 50–100 ha, 3) 1–500 ha, 4) 500–1000, and 5) >1000 ha.

Since the interest is in very broad patterns over hundreds of years, LANDMINE was run with minimal rules and assumptions. No topographic data was 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 all of western boreal Canada was determined by a combination of a literature review, a two-day workshop of fire regime experts, and another three years of collaboration among fire regime experts to finalize the details. For a full description and explanation of the LTFC map, see Andison (2018). See below for how these data were used to calibrate LANDMINE.

5.2 Spatial Data

LANDMINE uses 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) *<u>Create a single landscape snapshot with no cultural features</u>*. 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 by 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 were then used to define one of nine Weyerhaeuser-defined forest cover-classes that Weyerhaeuser uses for management planning, with the leading species (combinations) as follows:
    a. Pine (Pl)
    b. White spruce (Sw)
    c. Black spruce (Sb)
    d. Deciduous (Aw)
    e. Conifer-dominated Pl-mixedwood
    f. Conifer-dominated Sw-mixedwood
    g. Conifer-dominated Sb-mixedwood
    h. Deciduous-dominated Pl-mixedwood
    i. Deciduous-dominated Sw-mixedwood

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 was used to define four broad *seral* stages of stand development (consistent with the rules used by the provincial government) for each of the four forest cover-classes above 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 was the most recent AVI (Alberta Vegetation Inventory) data for the Weyerhaeuser FMA area. These data were provided by Weyerhaeuser. The area in each of the four seral-stages × nine 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.

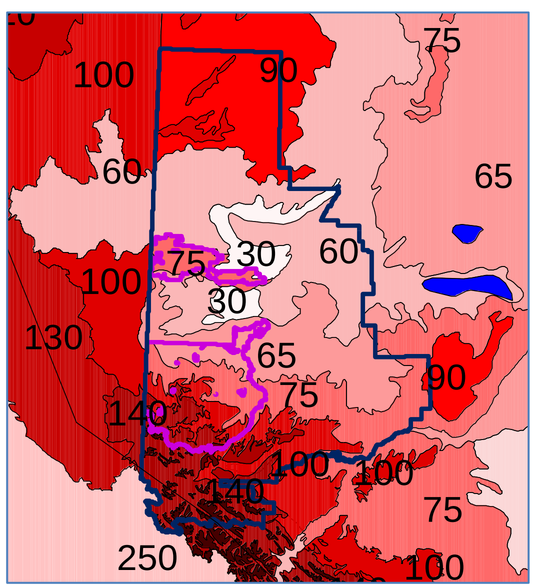
5.3 Model Calibration

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, topography, 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 2019a), 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. For example, on a 100,000 ha study area, how many years (on average) does it take for 100,000 ha to burn? Thus, during any given fire cycle, some areas will burn more than once, and others not at all.

Figure 4. Study area map showing the long-term-fire-cycles (years). The Upper Peace area is shown in dark blue and the Weyerhaeuser FMA in magenta.



Note that the final LTFC map generated by the expert process described by Andison (2019) differs from Figure 4 in two ways. First, the Dry Mixedwood NSR area LTFC was 45 years in the final report instead of 60, and the Peace River Parkland NSR area LTFC was 20 years instead of 30. Neither infliences the results of this study to any signficant degree.

As a side note, it is interesting to note the alignment of the FMA boundaries with the historical fire regime zones. Most prominently, the entire Saddle Hills part of the FMA to the north lies within an upland area with much higher estimated LTFCs relative to adjacent areas. The larger south management area captures the lower elevation, most productive parts of the subalpine to the south, and close to what would have been the historica forest-grassland interface to the north (Figure 4).

Using the average LTFC estimates from Figure 4 in the model would be inappropriate. We know that long-term fire cycle estimates include highly variable fire activity from one decade to the next. Thus, what the model required was an equation representing decadal probabilities of fire activity, based on historical data. In this case, decadal variability in the LTFC was captured by an equation representing historical decadal levels of historical fire activity in the Alberta foothills using a back casting technique (*sensu* Vilen et al. 2012). Essentially, this technique 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. Keep in mind that the LTFCs become the targets, so the only function of this model parameter is to approximate (historical levels of) variability around the LTFC.

In order to accurately reflect the range of LTFCs in the study area, the LTFC estimates were used as targets for the average level of disturbance in each of the ten fire regime areas in the larger modelling area. This was accomplished by adjusting fire ignition probabilities in each fire regime zone, using the original, 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. 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 from 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 model it in space and time – thus the calibration exercise.

After several weeks of this iterative calibration process, 100 landscape snapshots were captured, measured, and summarized to represent NRV (Table 4).

Table 4. Summary of the area modelled in this project, showing how ignition probability in LANDMINE was calibrated to achieve the desired historic LTFC targets.

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**

Note that the LTFC numbers used for this study area to calibrate this landscape for this project (Table 4) differ from the final numbers found in Andison (2018), and show in Figure 4. This is because the process of creating the LTFC map for the western boreal was a long-term iterative one that only finished in 2017, which was at least a year prior to a final commitment to the modelling assumptions used for this project. However, the differences are insignificant. The biggest change is that the LTFC of the Dry Mixedwood area shifted down from 60 years (in this LTFC version) to 45 years (in the final version)

(Andison 2019a). However, the Dry Mixedwood NSR was only a very small part of the Weyerhaeuser FMA (Table 4), all of which is ecotonal. In any case, the only other difference of note is that the LTFC for the subalpine NSR changed from 135 years to 140, which will have minimal impact on the seral-stage results. The LTFC change from 30 to 20 years in the Peace River Parkland will have no impact on the results.

5.3.2 Fire Size

The output from the fire regime workshop referred to above concluded that there was not yet enough data or evidence to define or defend specific, unique fire size distributions for the majority of the western boreal (Andison 2018). This group agreed on some maximum fire size numbers for some landscapes relevant to this study area, including 1000 ha in the Peace River Parkland, 3000 ha in the Montane, and 5000 ha in the Dry Mixedwood (Andison 2019a).

The strategy for fire size in the model was to reflect both the agreement on general trends, and that of specific fire regime zones. 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 = 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.

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% in fires 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 1996, 2012).

5.4 Running Landmine

For each of the 100 landscape snapshots generated by the model, non-spatial summaries of area each of the nine vegetation × four seral stage classes were compiled for a) the entire Weyerhaeuser area, b) the two different spatial areas of the FMA, c) woodland caribou herd areas, and d) natural subregions. Results were also summarized by the passive and active land bases (as defined by Weyerhaeuser) for the combined Weyerhaeuser areas.

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

6.0 Results

The results are organized into sections reflecting non-spatial vs. spatial patterns.

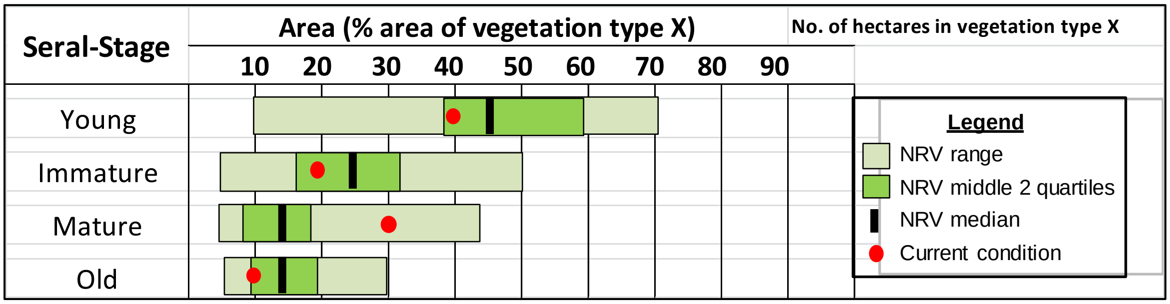
6.1 Non-spatial Results

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 the 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.

Quartiles not only simplify the output into a more visually intuitive form, but also allows viewing all seral stages of a given vegetation type at the same time. Reading the example shown in Figure 5 is as follows: First, each set of four quartiles represent all seral-stages of a specific vegetation type. Recall there are seven vegetation types, plus one that combines all forest into a single 'forest' class. 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.

In terms of the details of the graph, the width of the green bands (regardless of shade) captures the 100 model runs representing NRV, and the red dot is the current condition. So, in Figure 5, the red dot at 40 for *young* forest represents 40% of the 100,000 ha of (in this case) pine — 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.

Figure 5. Example of how the non-spatial modelling results are presented.

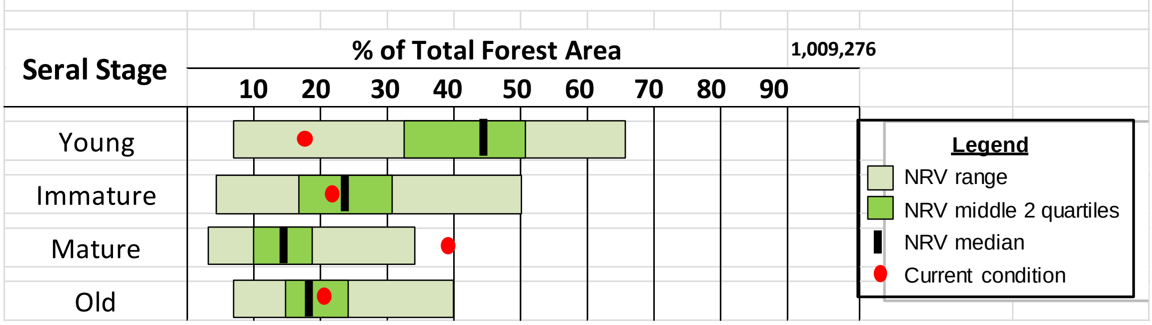


The NRV model run output are captured in *quartiles*, interpreted as follows. Each set of horizontal green bars represent the full range of the model output. For example, in Figure 5, no model runs created less than 10% and no more than 70% of young pine. The quartiles (bands within which exactly 25% of the data lie) are represented by the different shades of green (Figure 5). Quartiles are numbered in order from lowest to highest. So quartile 1 (Q1) is the light green band on the far left of each bar, quartile 2 (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 5). The dark black line between Q2 and Q3 is the *median,* which is the 50th percentile of the NRV data. Note that the medians in each figure will approximately (but not always exactly) add up to 100%.

6.1.1 Weyerhaeuser Overall

Overall, three of out of the four seral-stages of the Weyerhaeuser FMA forest areas were within NRV. The good news is that both the immature and old forest levels were not only well within NRV, but close to the historical median. However, the current level of mature forest was already well beyond anything observed from the modelling exercise, and the amount of young forest, while within NRV, was only at the 4th percentile (Figure 6). In other words, the model predicted young forest levels lower than the current level only 4% of the time. Moreover, when the mature and old forest levels were combined, the 60% currently on the landscape exceeded the maximum level generated from the historical NRV modelling exercise.

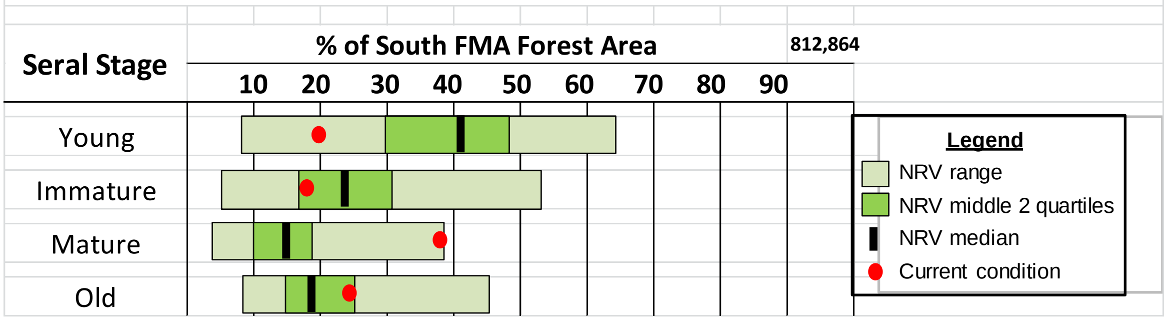
Figure 6. Historical Range of the Weyerhaeuser Grande Prairie FMA Area Forest



6.1.2 Weyerhaeuser FMA Areas

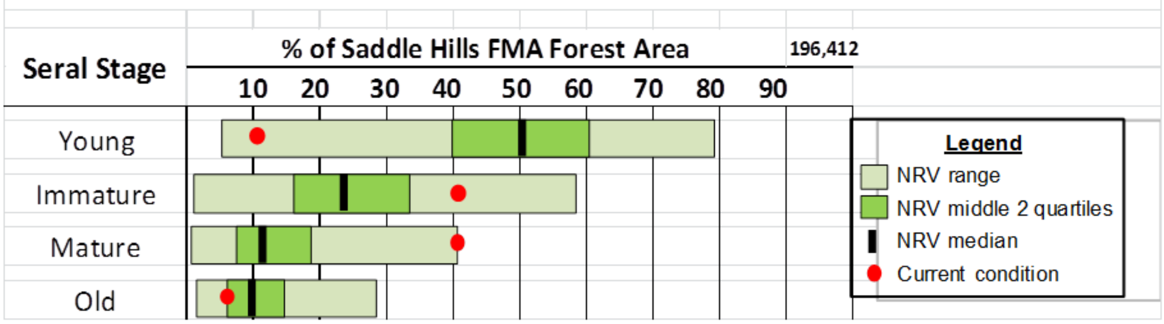
The patterns noted for the largest part of the Weyerhaeuser Grande Prairie FMA tenure area (the *South*) were very similar to those of the overall results. This is not surprising given the large influence of these data in the summaries of the overall picture for the Weyerhaeuser management area. As above, the current level of young forest (20%) was far below the median (41%) (Figure 7). In contrast, the 38% of mature forest was beyond anything observed from the NRV modelling output. However, both the immature and old forest levels were currently well within the historical range (Figure 7).

Figure 7. Historical Range for the South Part of the Weyerhaeuser Grande Prairie FMA



In the Saddle Hills Weyerhaeuser area, the relationship between NRV and current condition showed a similar pattern, but more acutely so. Just eleven percent of the Saddle Hills forest was young representing the 4th percentile, compared to 52% for the median of NRV (Figure 8). The current 41% of immature forest was on the high side, but well within NRV. In sharp contrast, the current level of 41% of mature forest was beyond the upper NRV threshold. The current old forest level was well within NRV.

Figure 8. Historical Range of the Saddle Hills Part of the Weyerhaeuser Grande Prairie FMA

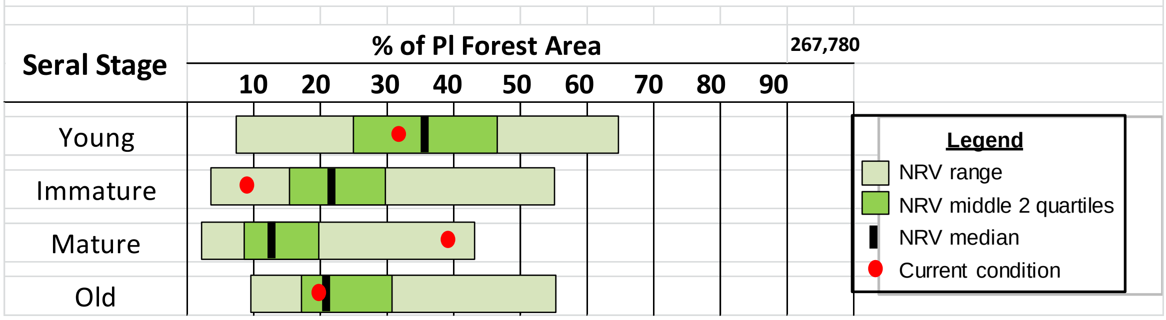


6.1.3 Major Vegetation Types

The following results break down the Grande Prairie Weyerhaeuser FMA area by eight of the nine Weyerhaeuser-defined forest types as per Section 5.2.1. The conifer-leading Sb-mixedwood class had less than 1000 ha, and was not reported here.

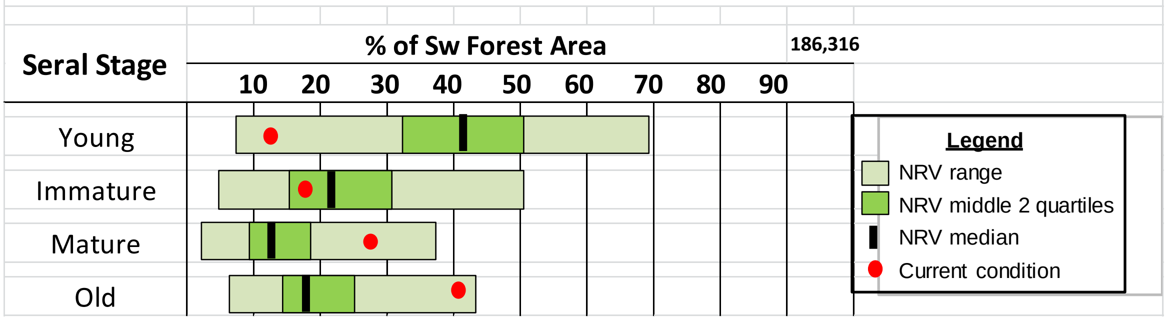
Pine-dominated forest levels were within NRV for every seral stage, but the pattern was an unusual one. For example, the current 39% of mature forest was at the 97th percentile of NRV, and the 9% immature forest was well below the median NRV level (Figure 9). However, both young and old forest levels were not only well within the middle two quartiles of NRV, but also fairly close to the NRV median (Figure 9).

Figure 9. Historical Range for Pine in the Weyerhaeuser Grande Prairie FMA



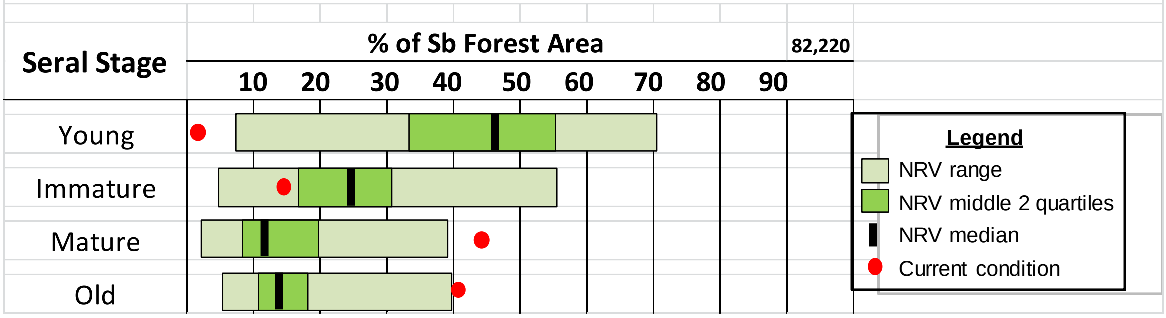
The current level of white spruce dominated forest on the Weyerhaeuser FMA area was significantly shifted towards older forest. For example, the 41% of old white spruce forest was almost beyond the 43% maximum NRV levels, and the current 28% of mature forest was only observed five percent of the time with the NRV landscape snapshots (Figure 10). Current levels of immature white spruce forest were well within NRV, but the 13% young white spruce was very near the lower end of NRV. In part, the reason for these trends was the decision to turn the succession module off in LANDMINE. In mixedwood forests, young stands often start out as hardwood and become mixedwood, and ultimately white spruce as they age. Thus the NRV results were likely over-estimating the historical levels of young white spruce, and under-estimating the historical levels of old white spruce. Applying these qualitative corrections would in fact decrease the gap between the current and historic conditions decreases.

Figure 10. Historical Range for White Spruce in the Weyerhaeuser Grande Prairie FMA



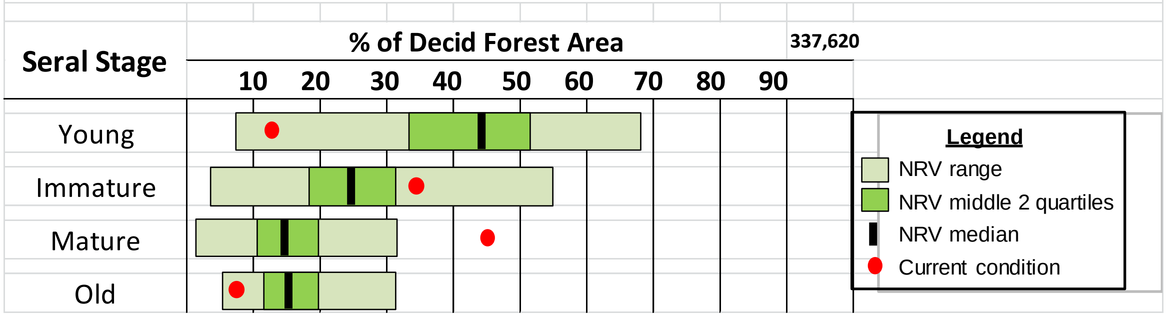
The current level of black spruce (Sb) dominated forests on the Weyerhaeuser FMA area was well beyond NRV for three out of four seral stages. The current two percent of young Sb forest was not only significantly lower than the NRV median, but also below the minimum level of 7% observed from the NRV simulation exercise (Figure 11). The two percent of young Sb forest represented only 1644 ha compared to the historical median of almost 38,000 ha. In contrast, the current levels of both mature and old Sb were both beyond the *maximum* levels observed by the NRV modelling exercise (Figure 11).

Figure 11. Historical Range for Black Spruce in the Weyerhaeuser Grande Prairie FMA



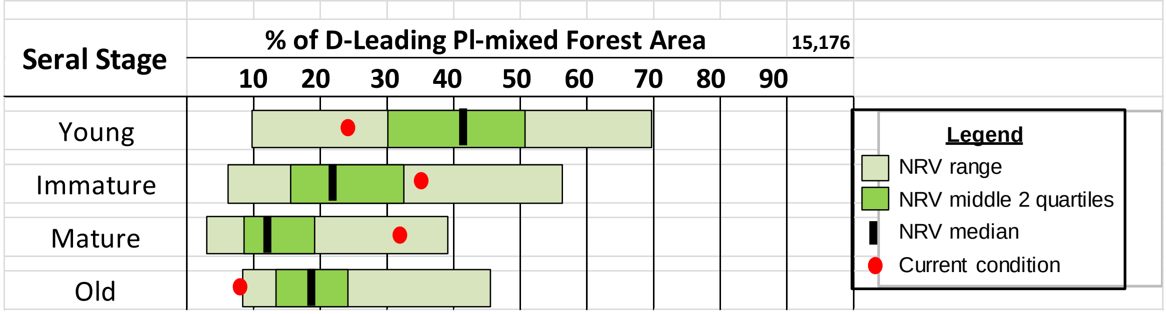
The pattern of the seral stages of deciduous forest on the study area was unique, and suggests that old hardwood-dominated areas are significantly under-represented on the landscape today. For example, the current level of old deciduous was 8%, which matches only the 7th percentile of NRV from the model output (Figure 12). At the same time, the amount of mature forest was well beyond NRV, and the amount of young deciduous forest was almost beyond the lower NRV threshold. However, recall that the succession module in LANDMINE was not turned on for these runs. Thus, the fact that there was very little old deciduous today is likely due to the fact that older stands dominated by hardwood tend to become mixedwood or white spruce as they age. The model thus over-represented the historical levels of old deciduous forest, which means the low current level is not likely a concern. However, since the model also under-estimated the amount of young deciduous forest, the current level of 13% was likely actually well below the lower bounds of NRV (Figure 12).

Figure 12. Historical Range for Deciduous in the Weyerhaeuser Grande Prairie FMA



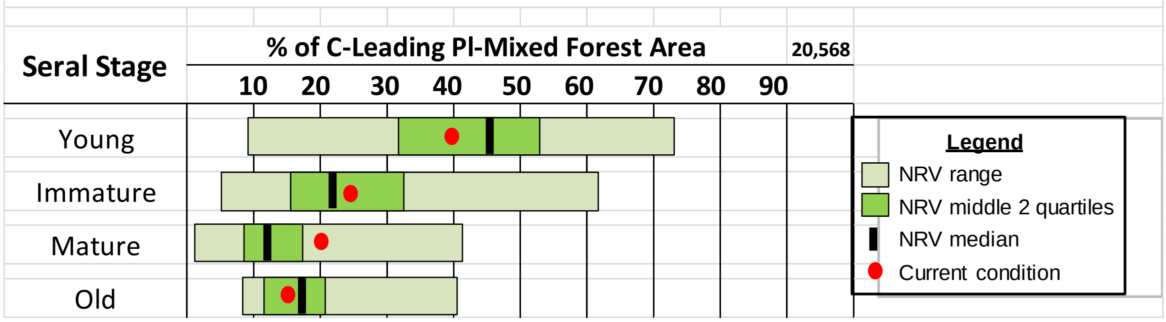
The current levels of deciduous-leading pine-mixedwood (DC-Pl) areas on the study area showed an unusual distribution. The high current level of mature forest contrasted sharply with the very low levels of old forest levels (Figure 13). However, this forest type was only represented by just over 15,000 ha, which is very small for a meaningful NRV analyses at landscape scales. The results were presented here as information only.

Figure 13. Historical Range for Deciduous-Dominated Pine Mixedwood in the Weyerhaeuser Grande Prairie FMA



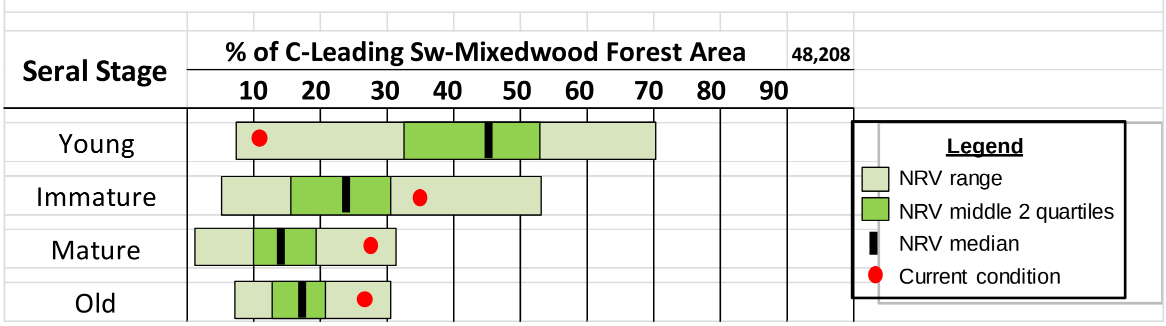
Current levels of conifer-dominated pine mixedwood (CD-Pl) were all well within NRV (Figure 14). In fact, the only current level (i.e., red dot) not in the middle two quartiles was the mature forest. However, as above, note that this forest type covered less than 21,000 ha, which is a very small area to be evaluating NRV patterns at landscape scales.

Figure 14. Historical Range for Conifer-Dominated Pine Mixedwood in the Weyerhaeuser Grande Prairie FMA



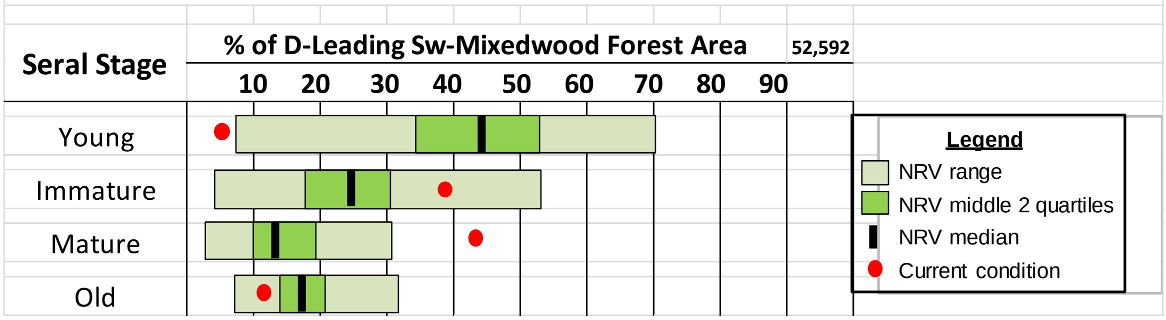
The seral stage patterns of the conifer-dominated white spruce mixedwood (CD-Sw) were similar to those noted previously. While the current conditions of all four seral-stages were within observed NRV, three were close to NRV extremes (Figure 15). Young forest current was at 11%, which was exceeded 99 out of 100 times by the NRV modelling exercise, and thus statistically) beyond the historic range. Similarly, the current level of mature forest represented the 96th percentile or NRV, and the current amount of old forest the 94th percentile (Figure 15).

Figure 15. Historical Range for Conifer-Dominated White Spruce Mixedwood in the Weyerhaeuser Grande Prairie FMA



The deciduous-dominated white spruce mixedwood (DC-Sw) seral-stage patterns were similar to those of pure deciduous areas. The current amount of both young and old forest were at or near the lower end of NRV, while the current level of mature forest was well beyond NRV (Figure 16).

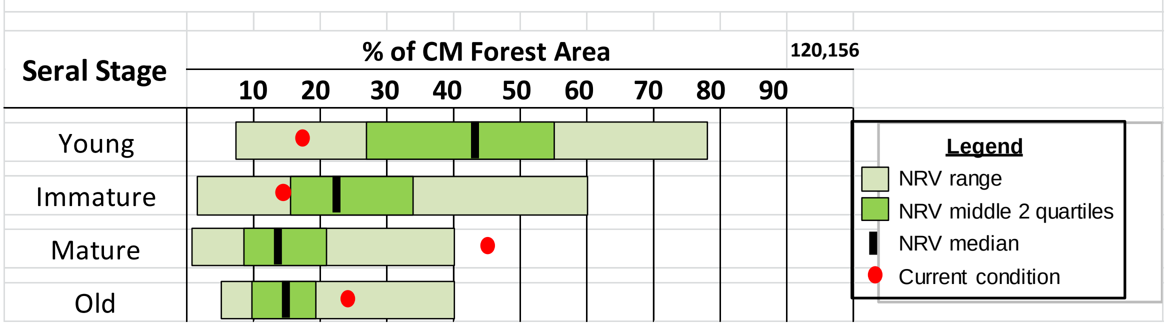
Figure 16. Historical Range for Deciduous-Dominated White Spruce Mixedwood in the Weyerhaeuser Grande Prairie FMA



6.1.4 Ecological Natural Subregions

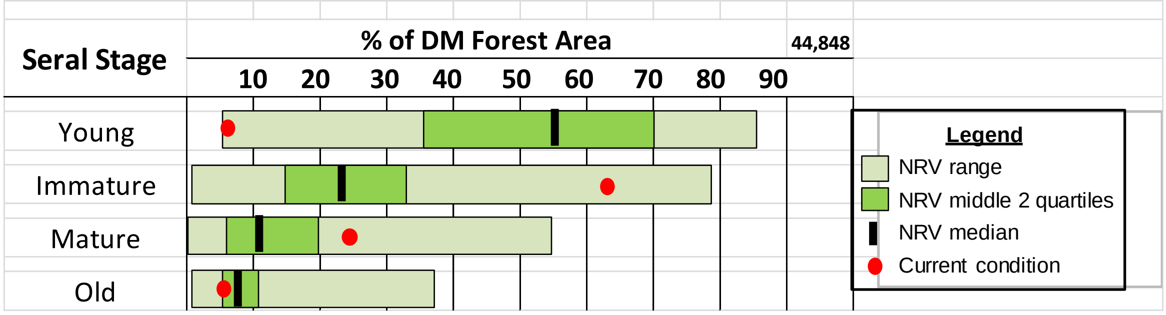
The patterns within each natural subregion (NSR) were similar to those noted in the previous section, although there were some noteworthy differences. The central mixedwood (CM) area had a historical LTFC of 65 years (Table 4), which created a significant amount of young forest. Young NRV in the CM area averaged 42% with a median of 43% (Figure 17). The current level of young forest in the CM area was 18%, which represented just the 7th percentile. The current old forest level (23%) was on the high end, but still well within NRV. However, the current mature forest level (45%) was well beyond the 40% maximum observed from the NRV modelling. The 14% currently in immature forest in the CM was just below the 25th percentile of NRV (Figure 17).

Figure 17. Historical Range for the Central Mixedwood NSR in the Weyerhaeuser Grande Prairie FMA



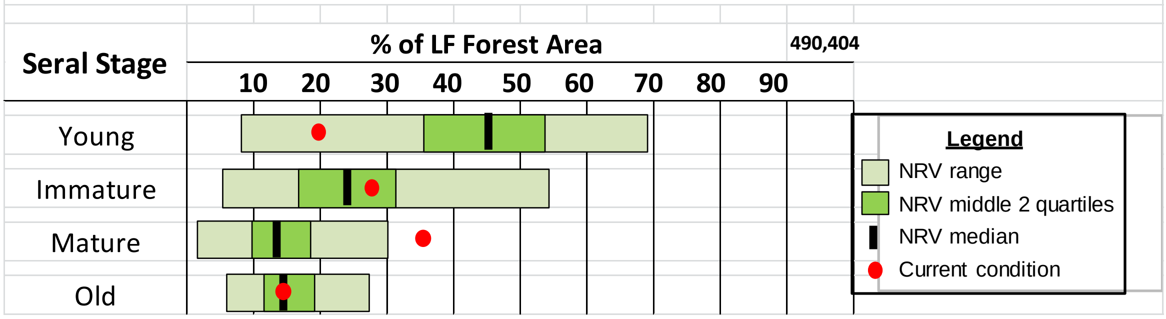
The average amount of young forest in the dry mixedwood (DM) natural subregion averaged 51% historically, with a median of 55% (Figure 18). The NRV runs only produced one landscape snapshot with lower young forest levels than the current level of 7%. The current levels of both immature and mature were both very high, but still within observed NRV. The current level of old forest in the dry mixedwood (6%) was just below the median (7%).

Figure 18. Historical Range for the Dry Mixedwood NSR in the Weyerhaeuser Grande Prairie FMA



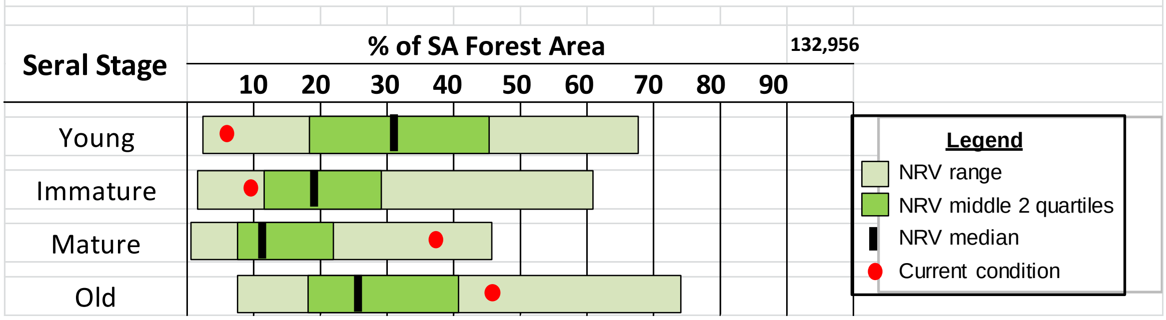
The lower foothills NSR within the Weyerhaeuser FMA area similarly had very low levels of young forest relative to NRV. And although the current level of 15% of old forest in the LF landed exactly on the NRV median, the current level of mature forest (36%) was well beyond the 30% maximum observed by the NRV modelling (Figure 19).

Figure 19. Historical Range for the Lower Foohills NSR in the Weyerhaeuser Grande Prairie FMA



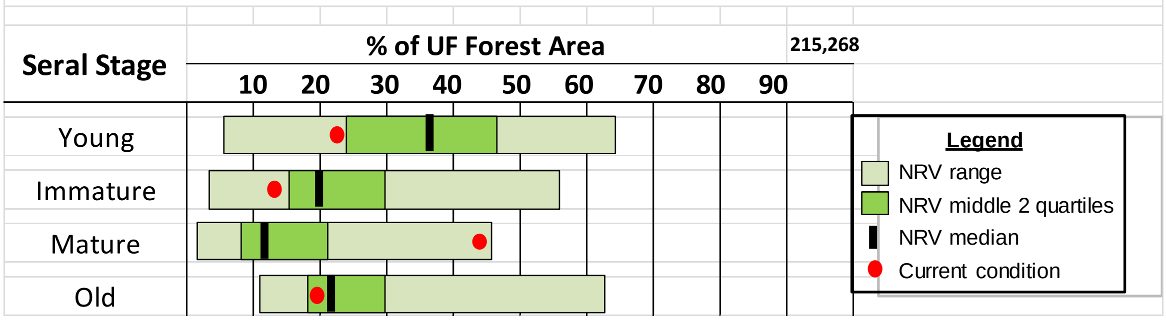
The subalpine (SA) area has the longest LTFC of any NSRs in the study area at 135 years (Table 4) — almost twice that of the CM NSR. As a result, the model generated the lowest levels of young forest (median of 31%) and the highest levels of old forest (median of 26%). Despite this, only six of the NRV model runs generated young forest levels lower than the 6% currently observed. Similarly, the current level of mature SA forest represents the 94th percentile of the NRV data, and the current level of old forest was in the fourth quartile of NRV. When mature and old forest levels were combined, the current level exceeded anything observed from the modelling exercise. Put another way, of the 133,000 ha of the Weyerhaeuser FMA area in the SA, 111,000 ha of it is older than 80 years.

Figure 20. Historical Range for the Subalpine NSR in the Weyerhaeuser Grande Prairie FMA



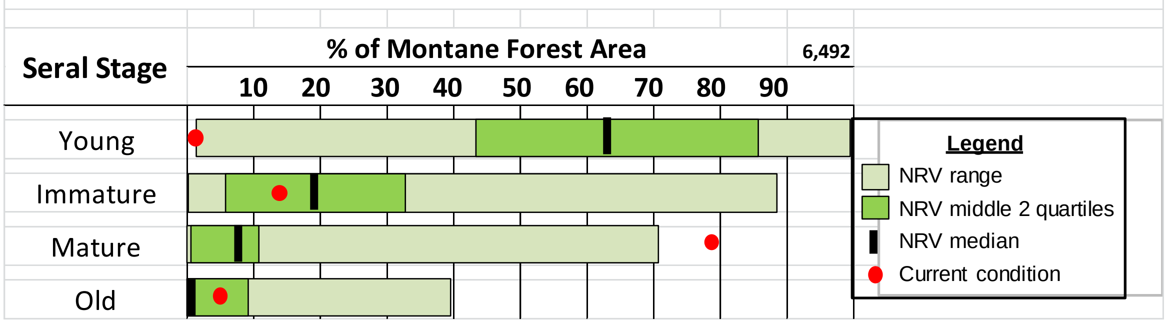
The upper foothills (UF) NSR is intermediate in terms of LTFC for the study area at 100 years (Table 4) which translated into median historical young forest levels of 37%, and median historical old forest levels of 22% (Figure 21). Young UF forest was currently 22%, which was well below the NRV median, but very close to the 25th percentile of NRV (Figure 21). Immature forest was currently 13% which was close to the 25th percentile of NRV, and the current level of old forest (20%) was close to the NRV median (22%). However, the 44% currently in the mature forest stage was statistically beyond NRV — and almost four times the NRV median (Figure 21).

Figure 21. Historical Range for the Upper Foothills NSR in the Weyerhaeuser Grande Prairie FMA



The montane NSR has a very low LTFC (Table 4) which in the modelling exercise generated a massive amount of young forest, and very little old forest (Figure 22). In contrast, the vast majority of the montane forest today is mature, and almost no young. It is important to keep in mind that the 6500 ha area of the montane NSR in the Weyerhaeuser FMA was not nearly large enough to be considering landscape-scale NRV metrics.

Figure 22. Historical Range for the Montane NSR in the Weyerhaeuser Grande Prairie FMA



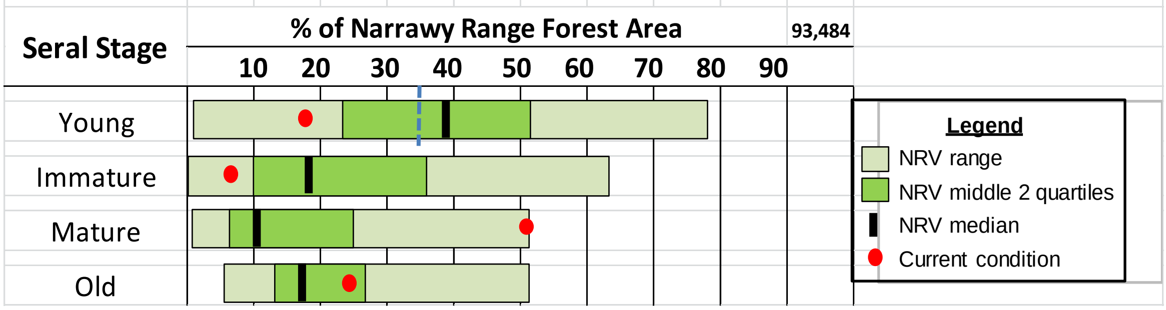
6.1.5 Woodland Caribou Ranges

Only two caribou ranges intersect with the Grande Prairie Weyerhaeuser FMA area in any significant way: Narraway and Red Rock.

Both the average and the median NRV for young forest from the modelling in that portion of the Narraway range within the Weyerhaeuser FMA was 39% (Figure 23). Of the NRV landscape snapshots generated in this study, only 43% met the requirement of at least 65% of the forest in a “recovered” state, or >40 years of age (Environment Canada 2012). In other words, less than half of the time, the

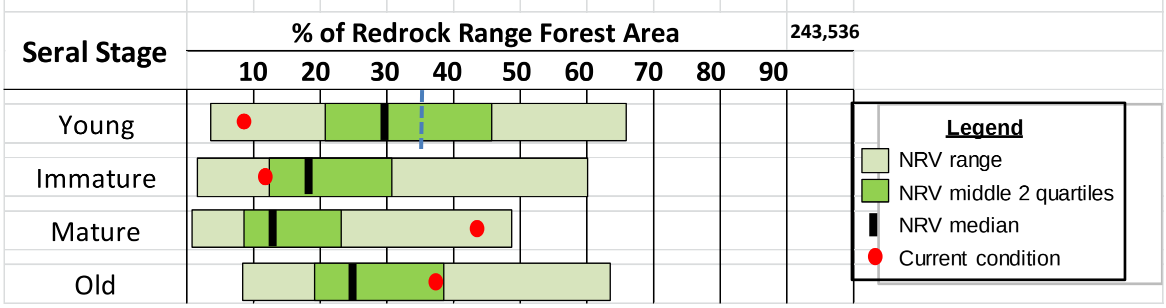
Weyerhaeuser portion of the *Narraway range* was historically unlikely to support a viable woodland caribou population as per the current federal guidelines. The current level of young forest (18%) was within NRV, and also well below the 35% upper threshold to support caribou defined by Environment Canada (Figure 23). However, the greater concern is the current massive level of older forest relative to NRV. Current levels of forest in the Weyerhaeuser part of the Narraway range older than 80 years are already beyond anything observed historically from the modelling exercise (75% versus the maximum NRV of 73%).

Figure 23. Historical Range for the Narraway Herd in the Weyerhaeuser Grande Prairie FMA **(the blue line represents the 35% upper threshold of "recovered" forest as per Environment Canada requriements)**



The seral-stage results of the Redrock caribou range in the Weyerhaeuser FMA were fairly similar. In this case, the NRV results suggested that the Environment Canada (2012) requirements for the Redrock range within the Weyerhaeuser FMA were met 57% of the time. The current young forest level of 9% was very close to the lower threshold of NRV, and the current level of mature was close to the upper threshold of NRV (Figure 24).

Figure 24. Historical Range for the Redrock Caribou Range in the Weyerhaeuser Grande Prairie FMA (the blue line represents the 35% upper threshold of "recovered" forest as per Environment Canada requriements)



6.1.6 Grizzly Bear Habitat

The Weyerhaeuser FMA has both core and secondary grizzly bear habitat. Consistent with previous results, the current level of young forest was on the lower end of NRV, and the current amount of mature forest was beyond the upper boundary of NRV (Figure 25). The current condition of the secondary habitat forest fared better. Although mature forest levels were currently above the 90th percentile of NRV, all four seral-stages were within NRV, and both immature and old forest within the middle two quartiles of NRV (Figure 26).

Figure 25. Historical Range for the Core Grizzly Bear Habitat in the Weyerhaeuser Grande Prairie FMA

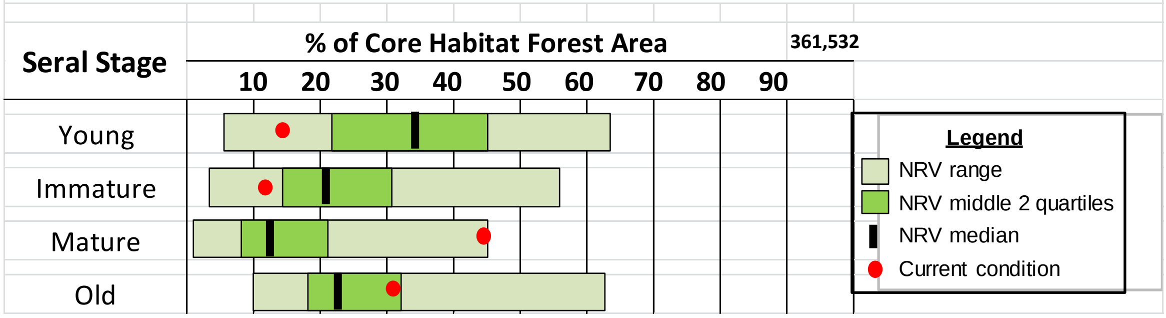
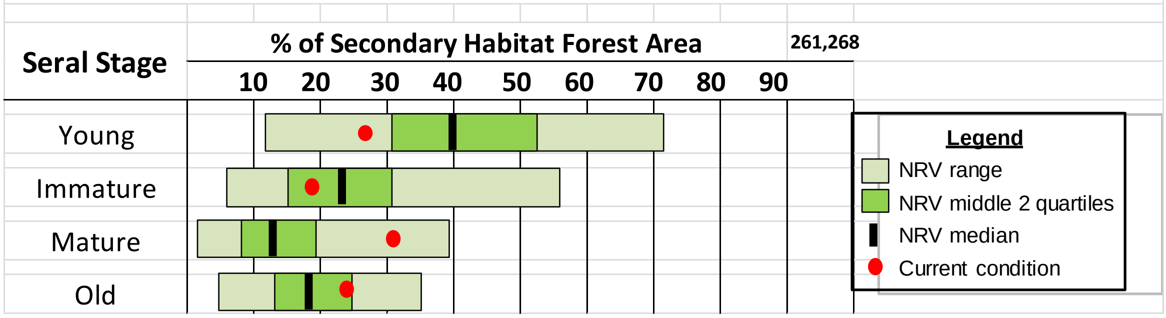


Figure 26. Historical Range for the Secondary Grizzly Bear Habitat in the Weyerhaeuser Grande Prairie FMA



6.1.7 Passive vs. Active Land base

Most forest management agencies in Canada must identify those parts of the forest within an FMA area that are 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, we obtained the active-passive map directly from Weyerhaeuser and used it to calculate NRV versus current condition (Figures 27 and 28).

Note that the NRV patterns for the two forest types were similar but not identical. This is interesting because neither one represents a single fuel-type, but rather a combination of several different ones representing a number of different unique fire regimes, each with a unique LTFC.

The difference in current conditions between the two areas was far more significant, and most obvious at the extremes. Active young forest on the Weyerhaeuser FMA area currently was 20% (Figure 27), compared to just 7% for the passive young forest. The 20% of forest currently in the old seral-stage in the active land base was far less than the 28% of old passive forest. The current level of 38% mature forest in the active land base was somewhat lower than the 44% currently in the passive land base, but both were well beyond the upper end of NRV. Current levels of immature young forest were almost identical, and well within NRV.

Figure 27. Historical Range for the Active Land Base of the Weyerhaeuser Grande Prairie FMA

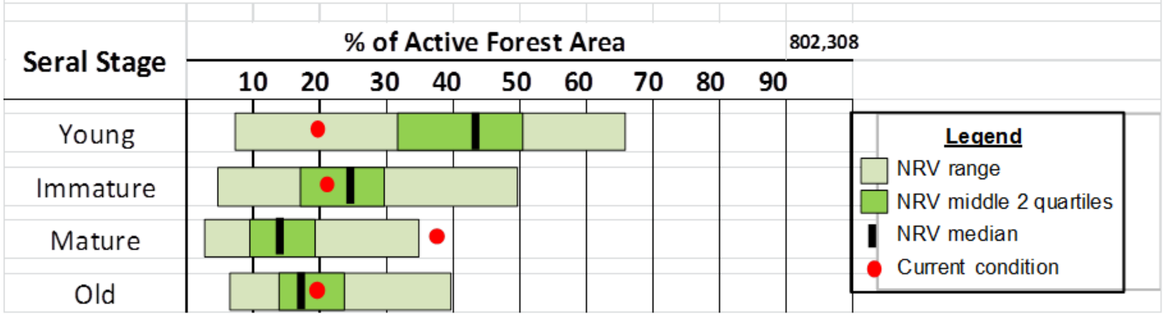
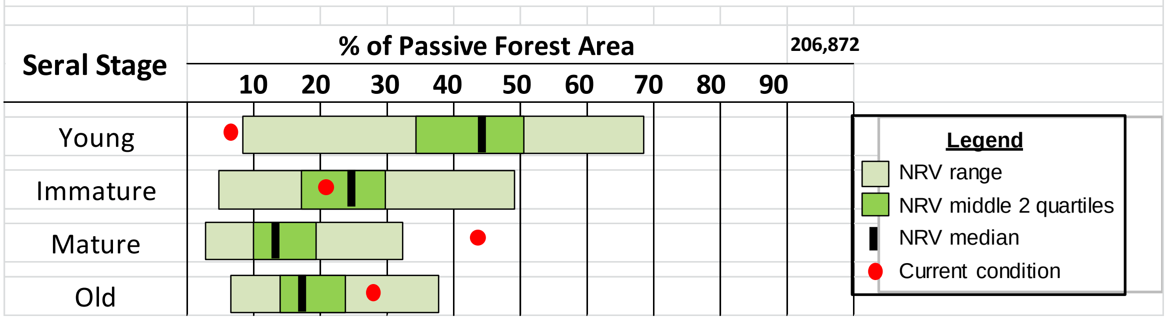


Figure 28. Historical Range for the Passive Land Base of the Weyerhaeuser Grande Prairie FMA



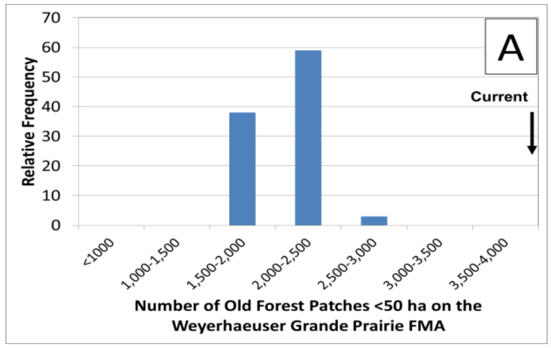
6.2 Spatial Results

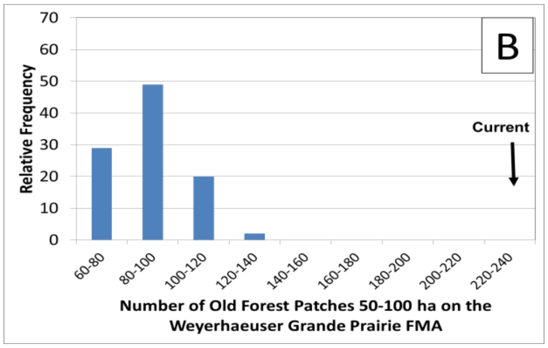
As a reminder, as per Weyerhaeuser's requirements, the results for five patch sizes of old forest are presented here: <50, 50–100 ha, 100–500 ha, 500–1000 ha, and >1000 ha. Moreover, a "patch" in this case captured only that portion of NRV or current condition that lies only within the boundaries of the Weyerhaeuser FMA areas. Large forest patches that extend beyond the boundaries of the Weyerhaeuser FMA area were captured by the model, but not reported. Results are reported here for the total Weyerhaeuser area, and the two spatially distinct management areas.

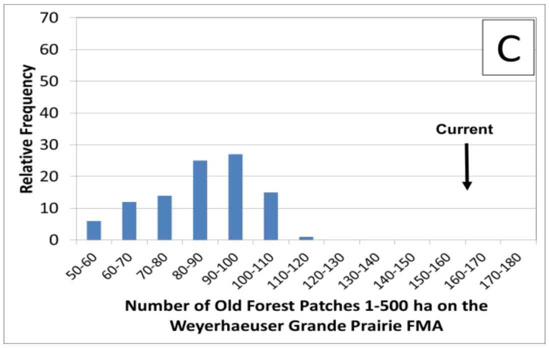
6.2.1 Weyerhaeuser FMA Area

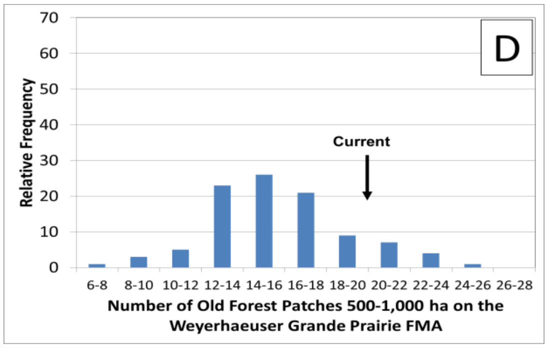
The number of very small (i.e., <50 ha) old forest patches on the study area ranged between 1674 and 2613 historically, which was well below the 4033 observed today (Figure 29A). The 233 old forest patches currently observed between 50–100 ha was also well beyond NRV (Figure 29B), as was the 160 old patches 1–500 ha (Figure 29C). Current levels of old forest patches 500–1000 ha, and >1000 were both within observed NRV (Figures 29D and 29E).

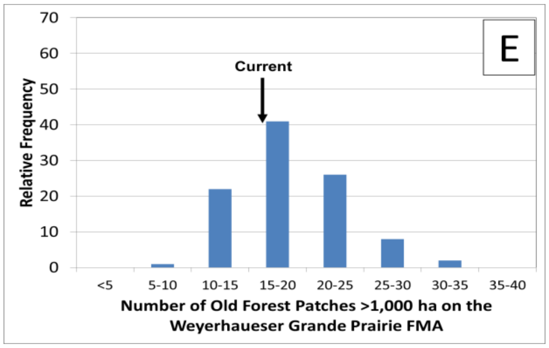
Figure 29. NRV (blue bars) and current condition (black arrow) of old forest patch sizes on the Weyerhaeuser Grande Prairie FMA area. Top right (A) is all old forest patches <50 ha. Middle left (B) all old forest patches 50–100 ha. Middle right (C) all old forest patches 1–500 ha. Lower left (D) all old forest patches 500–1000 ha. Lower right (E) all old forest patches >1000 ha.







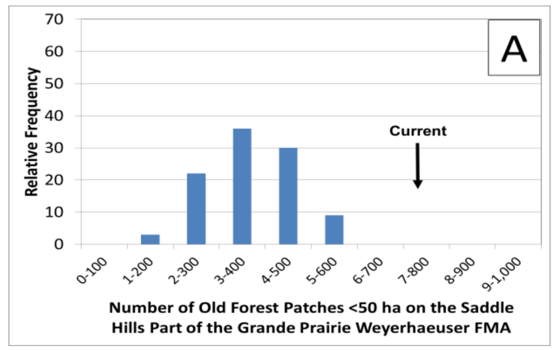


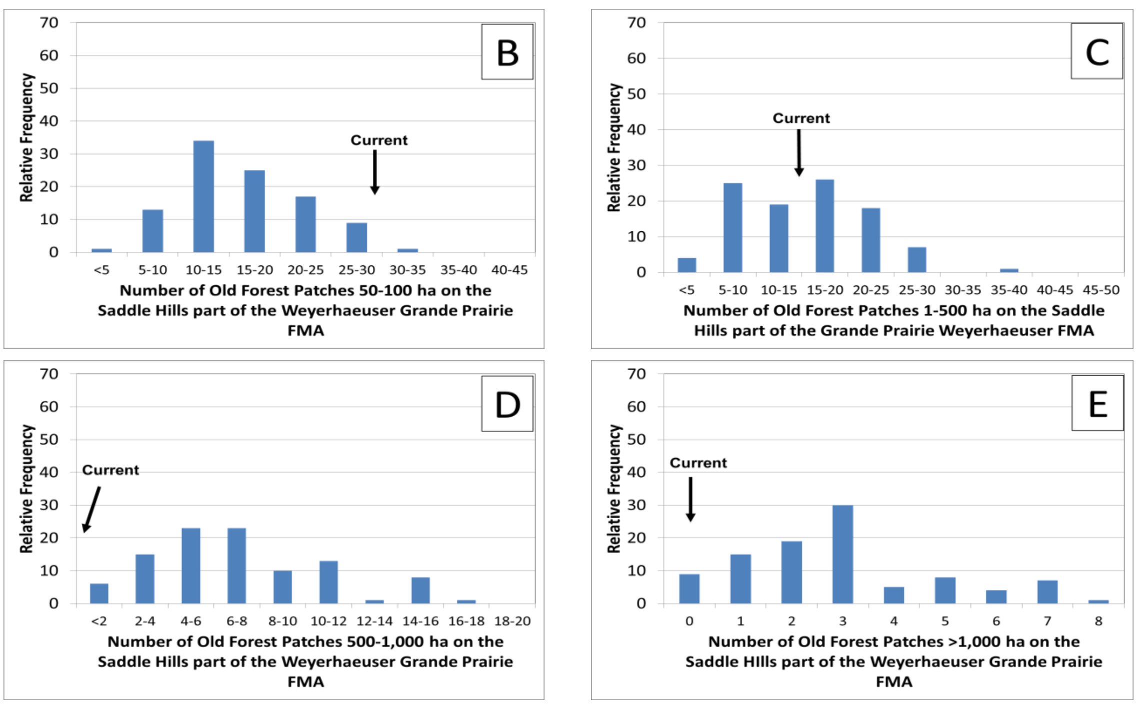


6.2.2 The Saddle Hills Management Area

At 211,000 ha, the Saddle Hills area is the smaller of the two FMA areas, which was reflected in smaller numbers of historical old forest patches overall. The number of very small (i.e., <50 ha) old forest patches ranged between 191 and 561 historically, which was below the 721 observed today (Figure 30A). The 29 old forest patches currently observed between 50–100 ha was almost beyond the maximum of 32 generated by the NRV modelling (Figure 30B). Current levels of old forest patches 1–500 ha were very near the NRV median (Figure 30C). There are currently no old forest patches larger than 500 ha on this landscape, in contrast to that suggested historically in Figures 30D and 30E.

Figure 30. NRV (blue bars) and current condition (black arrow) of old forest patch sizes on the Saddle Hills part of the Weyerhaeuser Grande Prairie FMA area. Top right (A) is all old forest patches <50 ha. Middle left (B) all old forest patches 50-100 ha. Middle right (C) all old forest patches 1-500 ha. Lower left (D) all old forest patches 500-1000 ha. Lower right (E) all old forest patches >1000 ha.

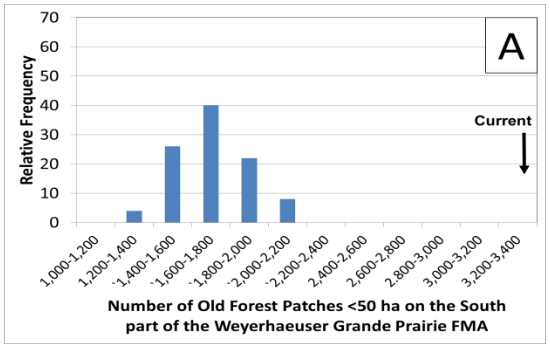


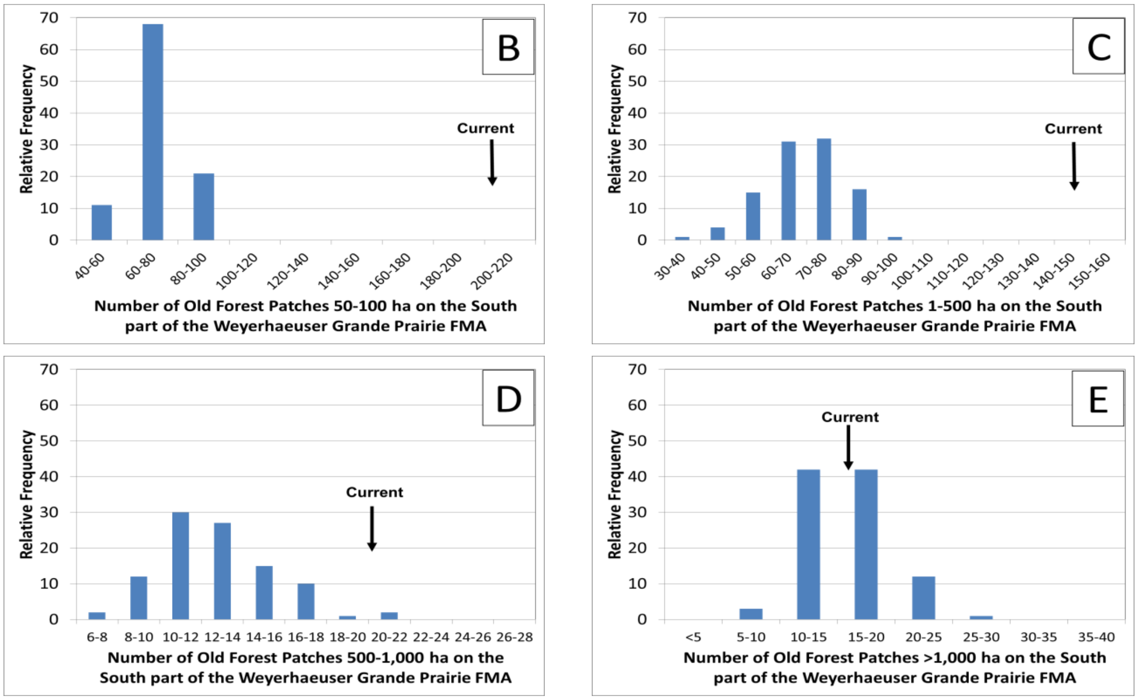


6.2.3 The South Management Area

Weyerhaeuser's South management area is fairly large at 907,000 ha. The number of very small (i.e., <50 ha) old forest patches on the Main ranged between 1337 and 2045 historically, which was well below the 3312 observed today (Figure 31A). The 204 old forest patches currently observed in 50–100 ha was well beyond the upper bound of NRV (Figure 31B), as was the 145 old forest patches currently observed in the 1–500 ha range (Figure 31C). Although within NRV, the 20 old forest patches 500–1000 ha was close to the upper NRV boundary (Figure 31D). Lastly, the 16 large (>1000 ha) old forest patches currently observed lands exactly on the NRV median from modelling (Figure 31E).

Figure 31. NRV (blue bars) and current condition (black arrow) of old forest patch sizes on the South part of the Weyerhaeuser Grande Prairie FMA area. Top right (A) is all old forest patches <50 ha. Middle left (B) all old forest patches 50–100 ha. Middle right (C) all old forest patches 1–500 ha. Lower left (D) all old forest patches 500–1000 ha. Lower right (E) all old forest patches >1000 ha.





7.0 Discussion

7.1 Overall Results

Spatial modelling exercises such as this generate such a large amount of output. This is an extraordinary opportunity to be able to explore pre-industrial landscape patterns in detail, but also a challenge to identify the most relevant signals. Towards the 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 old forest today relative to historical conditions***. The overall current level of old forest is actually within NRV, and creates a modest buffer against the inevitable natural disturbance events such as wildfire and insect outbreaks. Thus — *considered in isolation* — current overall old forest levels are at or near the 3rd quartile, which is not a concern. However, old forest levels for some parts of the landscape are already beyond NRV (i.e., old passive forest). Of greater concern is the fact that the current level of mature forest is beyond or very close to the upper bound of NRV for the entire study area. Consider that, barring significant increases in disturbance levels, inventory age data suggests that the majority of mature forest will shift to old forest in the next 10–20 years. In other words, this landscape is unbalanced 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 degree to which the shift from mature to old forest from this point forward depends on a) how much disturbance will take place, and b) where and how. For the sake of argument, let us start with a business-as-usual scenario in which nothing changes as regards policies and practices and project forward another 20 years. Recall that the 18% of young forest (<40 years of age) represents the 4th percentile of NRV. For context, the NRV median is 2.5 times higher at 44%. If we use the disturbance levels of the last 40 years as a benchmark for the future, we know that an average of (18%/40 years =) 0.45% of the landscape has been disturbed each year over at least the last 40. So, under this disturbance scenario, in another 20 years, that will convert (20 × 0.45 =) 9% 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 efforts to control them (Flannigan et al. 2000), which will a) increase the overall level of disturbance, and b) 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 triple that of the last 40 years, the amount of old + mature forest will still be beyond NRV in 20 years. However, under this scenario one must account for the potential catastrophic social and economic cost of those additional fires. So if anything, a more realistic future scenario for this landscape poses far greater challenges and risks than a simplistic one.

The implications of the spatial results are less clear. The contrast between the results from the two Weyerhaeuser management areas is fairly sharp. More specifically, the fact that the Saddle Hills area had no old forest patches of even moderate size (i.e., >500 ha) contrasts with the fact that the current number of large old forest patches was well within NRV on the South area. It is important to keep in mind that the NRV results were tailored specifically for each landscape, so it is not possible to blame landscape size on the discrepancy.

One possible alternative explanation for the discrepancy is any differences in spatial feature accounting methods or assumptions. The spatial data for the current condition calculation were provided by Weyerhaeuser, so the specifics of how a "patch" was defined is unknown, or whether the data or assumptions differ in quality or provenance between the two management areas. It is also important to note that the maximum patch size we captured was >1000 ha, and only by a simple count. The results in Figure 31D count a single 1001 ha patch, and a 100,001 ha patch the same. In other words, perhaps we did not have the right size classes to fully evaluate this pattern.

It is also possible that the Saddle Hills area has been more aggressively managed for a longer period of time via all human influences combined. However, the fact that the current level of young forest in the Saddle Hills (11%) is almost half that in the South area (20%) does not support this hypotheses. Another possibility is that the Saddle Hills has significantly more activity from the energy sector. Pickell et al. (2013 and 2015) found that despite the fact that the disturbance *footprint* of the energy sector was quite low, the fact that it was spatially ubiquitous means that the impact on the resulting landscape patterns was far beyond that of forest management. In other words, maybe the Saddle Hills has a much higher density of linear features, installations, and roads. A final possibility is that there has been a long-term dedicated effort to preserve larger old forest patches in the South area through planning and management.

In the end, the only way of understanding the impact of each of these potential factors on old forest patch size calculations is to conduct a more comprehensive and specific spatial analysis than this study was intended to provide.

7.2 The Details

The specifics of how NRV compares to current condition for the Weyerhaeuser 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 is already beyond NRV was surprising. The amount of passive forest older than 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 20 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 this part of the landscape.

The second surprise was that even on the so-called *active* portion of the land base, old and mature forest levels are still very high and young forest levels very 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) or 3) higher LTFC assumptions than used in this study. The low level of young active forest suggests that harvesting levels on this part of the land base has 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 informative. The current level of "recovered" forest (>40 years of age) was 82% for the Narraway range, and 91% for the Red Rock, both well beyond the 65% minimum required by federal guidelines. However, it is important to understand that these results only capture habitat from a non-spatial perspective and does not include the impact of linear features and the associated buffering. Having said that, the pattern of NRV for this caribou range is informative. For example, the Environment Canada (2012) requirements for a minimum of 65% of the landscape in a recovered state (i.e., at least 40 years of age) were met only 43% of the time for the Narraway range, and 57% of the time for the Red Rock. This suggests that these areas did not support woodland caribou 57% and 43% of the time respectively over the last several thousand years — assuming the Environment Canada (2012) habitat model correctly captures caribou requirements.

These results suggest one of three explanations:

a) One or more 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 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 known quotes about modelling is from George Box (1979): "*all models are wrong, but some are useful*". What he meant by that 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%, 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 did not change.

In the end, the LTFC maps clearly represent 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 impact of model output on different input assumptions, 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; 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 regards to current condition for the non-spatial results (i.e., the red dots), the 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 decreases in accuracy, and increases in bias (Andison 1999a, 1999b). It may also be true that the data provided by Weyerhaeuser at the time is now outdated.

As regards the calculation of current condition for patch sizes, there are two challenges. The first challenge 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) 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 the patch sizes is more daunting—how does one integrate and compare the impacts of forest edges of different sources and vintages? For example, if/how do we different edges associated with highways to that from a bush road, to that from a large, new seismic line, to 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 the new ABMI data.

7.4 Implications

In theory, a landscape that has moved / is moving beyond NRV 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 NRV 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 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, these risks will only increase. Note that this risk (ironically) 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 and/or shifts in ecological/habitat types. To demonstrate, Table 5 shows the current area in each of the four seral-stages for each of the eight 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 (dark green), the 95th percentile (any green), beyond the 95th confidence interval (light red), or beyond NRV (dark red) (Table 5). For context, each and every NRV landscape snapshot generated from the modelling exercise would be (light or dark) green for all 32 cells.

Table 5. Comparison of NRV to current condition for 32 major ecotypes for the Grande Prairie Weyerhaeuser FMA area. The area in each cell represents the current number of hectares in each type, and the colour code represents how it relates to NRV from the model output.

Seral-Stage	Species Type							
	Pine	Sw	Sb	Aw	Mix Sb	Mix Pl	Mix Sw	DC-Sw
Young	84,618	24,614	1,816	42,513	2,095	8,279	5,354	3,041
Immature	23,565	33,281	11,617	113,861	3,144	5,050	16,808	20,527
Mature	104,970	52,423	35,488	155,367	2,817	4,206	13,271	22,581
Old	54,627	75,998	33,299	25,879	728	3,034	12,775	6,443

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

The visual patterns from Table 5 alone are telling. Of the 32 different ecotypes, the current conditions of 17 (or 53%) are green. Of those, only seven (22%) are within the middle two quartiles of NRV (i.e., the dark green cells) and another 10 ecotypes (or 31%) are within the 95th percentile of NRV (which includes both the dark and light green cells). The current conditions of another eight ecotypes (or 25%) are already beyond NRV (i.e., dark red). Of even greater concern is the fact that the last ten (or 31%) ecotypes are within the outer boundaries of NRV. And in the absence of significant changes to forest land management policy and/or practice, many of the ecotypes on the Weyerhaeuser landscape will inevitably trend beyond NRV in the near future (Table 5).

When the results in Table 5 are translated into hectares, almost exactly half of the Weyerhaeuser FMA landscape is either beyond, or almost beyond, anything experienced historically.

From an ecological perspective, Table 5 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 43,000 ha historically in the study area, compared to an unprecedented 1816 ha today, which is well below minimum NRV levels. Similarly, young hardwood, mixed spruce, DC-spruce, mix Sb, and white spruce are all below or close to the lower threshold of NRV. The under-representation of one or more ecotypes across a large landscape should be cause for concern. 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 at 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 entire 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 2017).

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, a large new seismic line, or even 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 in Section 6.2 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 5 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-called ‘passive” landscape. Although it may be well recognized that wetlands provide significant ecological benefits to the boreal ecosystem, we have very little understanding of the details of those dynamics over time and space, particularly as it relates to wildfire. Given that wetlands account for up to 30% of the study area, our collective ignorance of these details contrasts sharply with our lack of research investment in this area.

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 in the future in terms of disturbance planning under business as usual 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 if or how future landscapes might look like under alternative policy/practice assumptions. Spatial modelling technology now 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 collaborative between forest and fire management. In the short term, any steps towards collaboration between these two otherwise independent government agencies can only be a positive contribution as regards addressing many of the regulatory / 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 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. In the bigger picture, there exists no alternative defensible landscape-scale benchmark for sustainability than (even adapted) pre-industrial conditions.

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 decades to shift beyond their historical range. The responses of the resident species to such deviations may take even longer to be observable. As a result, the implications of policies and practices based on fine-filter values are — almost always — only obvious to us 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 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, and thus social and economic values as well) 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, largely in response to the degree to which species or values get attention — in a negative sense. 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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