FINAL REPORT

Understanding Historical Landscape Patterns on the Millar Western Forest Products FMA Area in Alberta

Final Report

fRI Research Healthy Landscapes Program

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EXECUTIVE SUMMARY

This project was a spatial modelling exercise that created coarse-scale, pre-industrial landscape metrics for the Millar Western FMA area in Alberta. The primary goal was to understand if, or in what ways, the current conditions of the FMA area align with the historical, pre-industrial "natural" range. The results suggest that parts of the landscape are now beyond its historical range. More specifically, the amount of immature (40–80 years) was in many cases well beyond the upper natural range of variation (NRV) threshold, and the overall amount of both young (<40 years) and old forest was close to or beyond the lower NRV threshold.

Using black spruce dominated forest areas as a surrogate for "passive" areas, the results suggest that passive forest areas were less well aligned with NRV. More specifically, the amount of young forest was not only well below the NRV threshold, and also much lower than all other forest types.

The lack of both the old and young forest types is the greatest concern ecologically. While the ecological benefits of old forest are well known, a large number of specialized species are dependent on disturbance, creating a smaller, but unique diversity peak in biodiversity within a few years after disturbance thanks to the sudden physical, chemical, and environmental changes. Many parts of this landscape have been experiencing disturbance levels near or below the lower end of NRV for several decades, which minimizes opportunities for disturbance-specialist species.

If overall disturbance levels are not increased, the amount of older forest will continue to increase, resulting in higher risks to natural disturbance vectors such as wildfire.

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 soil conservation, toxin filtration, carbon cycling, fish and wildlife habitat, food, pharmaceuticals, and timber (Davis 1993).

Under the auspices of this evolution, 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. 1992, Grumbine 1994, Long 2009). The theory is 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 to planning and management programs at all levels and scales. Thus, defining the historical range of various ecosystem patterns is a 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 in time (Turner and Dale 1991, Payette 1993) and space (Andison and McCleary 2014). This means that historical levels of old forest are also likely to be both highly dynamic and spatially variable.

In the absence of detailed and repeated historical data and/or photos, the only means left to explore the dynamics of forest ecosystem patterns at the landscape scale is spatial simulation modelling. In its simplest form, spatial models allow us to explore how known (observed, recorded) probabilities of key variables intersect in time and 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 describes a modelling process by which we generated multiple possible historical landscape scenes, summarized their patterns, and compared those to the current landscape condition for the Millar Western FMA area. The larger modelling project is LandWeb; *Landscape dynamics of Western Boreal Canada*. *Note that this report is a compilation of chapters by different authors.*

1.0 Goal

D.W. Andison

The goal of the LandWeb project is: ***to understand some simple pre-industrial landscape-scale patterns in the western boreal forest 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). This report includes the results for the Millar Western FMA area.

2.0 Desired Conditions and Outcomes

D.W. Andison

3.1 Indicators

LandWeb project partners collectively identified two main classes of output/indicators as part of this project; 1) the area in each seral-stage × major vegetation types, and, 2) patch sizes of old forest × major vegetation types. Through a consultation process as part of this project, the LandWeb partners agreed to the following technical protocols:

- ***Major vegetation types*** were defined by polygons with at least 80% leading species of black spruce, white spruce, pine, deciduous, or fir (*Abies* spp.). All other forested areas that did not meet the 80% rule were classified as mixedwood.
- ***Seral stages*** were defined by the government of Alberta (GoA) provincial standard, and agreed to by everyone: young (<40 years), immature (40–80 years), mature (81–120 years), and old (>120 years).

In terms of old forest (i.e., >120 year old) patch sizes, the LandWeb partners also agreed that this project should report on the following patch sizes; >100 ha, >500 ha, >1,000 ha, and >5,000 ha. Patches should be reported by all forest types combined.

The LandWeb partners also asked to have NRV results summarized within several different geographic boundaries including a) jurisdiction (including the Millar Western FMA area), b) ecological natural sub-regions (NSRs), and c) existing caribou habitat range areas.

3.2 Current Conditions as a Reference Point

The relevance of NRV modelling output is increased significantly when it is compared to the current condition since this provides a relevant reference point in time. These data must be provided in exactly the same format, using exactly the same rules as defined above.

In theory, current condition data exist in the form of inventories and updates. However, for the purposes of this project, the most recent data are notoriously challenging and time-consuming to a) acquire and b) summarize in a universal format. This is only magnified by the fact that the study area includes five different provincial / territorial jurisdictions, 15 different forest management areas, multiple provincial and federal parks, and provincially-managed areas. Moreover, the vintage of the most recent updates varies considerably across the study area. Acquiring and compiling these spatial data from scratch would have exceeded the entire budget of this project.

Instead, we took advantage of an existing initiative to compile forest inventory data from across Canada. The CASFRI (Common Attribute Schema for Forest Resource Inventories) is the first and only known initiative to collect and standardize inventory data from multiple jurisdictions across Canada (Cosco

2011). Although this database was not 100% complete, and some of the data were outdated, it still saved us considerable time and costs. We acquired outstanding data directly from partners.

3.3 Creating a Pre-Industrial Condition Baseline

Given that the goal of the modelling is to construct the NRV, the spatial data involved need to be free of all industrial human influence, including permanent and semi-permanent land use changes (e.g., infrastructure, agriculture), harvesting, and fire control. This can be done in two ways. Some NRV modelling exercises start with an existing landscape — complete with anthropogenic influences — and run the model forward hundreds to thousands of years to *fill in* the areas influenced by human activity. Alternatively, it is possible to re-create a single natural vegetation conditions on a single landscape scene *via* a GIS exercise that uses the following, hierarchical, rules: 1) historical (pre-disturbance) vegetation information in digital format, 2) historical (pre-disturbance) vegetation information from available maps, 3) rules and/or an algorithm that calculates the most likely vegetation type of missing polygons based on neighbours. For this project, we chose to go with the second option.

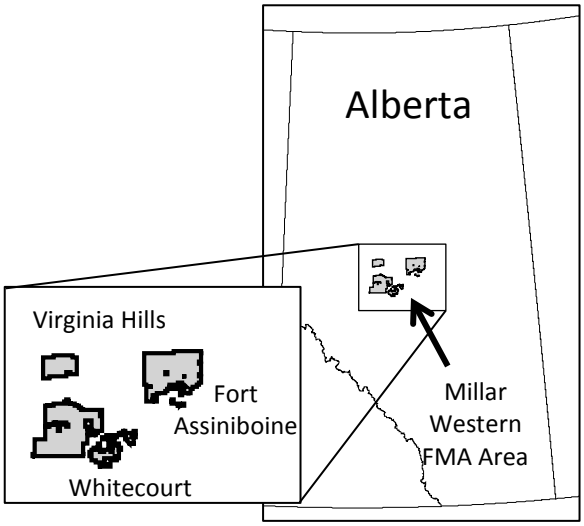
To create an initial pre-industrial landscape, we first obtained the oldest digital version of the forest inventory (with the least amount of cultural disturbance). Then we used digital data, records, and maps to replace cultural features with pre-disturbed vegetation types. Any remaining culturally modified polygons were filled with the age and cover-type attributes of the adjacent polygon with the greatest length shared boundary. Thus, all towns, roads, cut blocks, mines, and other human developments were replaced by attributes of the last known or the most likely forest type. The “natural” pre-industrial snapshot created by this process still included biases and inaccuracies from a) fire control b) using data from different eras, and/or c) aging errors from forest inventories, all of which could influence the subsequent model output for centuries. To eliminate this risk, the model was run forward several thousands of years before landscape snapshots were collected and measured.

4.0 Study Area

D.W. Andison

The area of concern for this report was the Millar Western FMA area, covering a total of 441,000 ha in multiple pieces, generally in three groups. The Virginia Hills area is 51,000 ha, the Fort Assiniboine 162,000 ha, and the Whitecourt area almost 228,000 ha (Figure 1). The largest two individual areas cover 187,000 ha, and 161,000 ha (42% and 36% of the FMA area respectively).

Figure 1. Study area map showing the Millar Western FMA area.



Ecologically, most of the FMA area is Lower Foothills natural subregion (NSR) (69%), with 26% Central Mixedwood, and just 5% Upper Foothills (Table 1).

Table 1. Summary of Millar Western FMA area by natural subregion (NSR)

NSR Name	FMA Area	
	Hectares	%
Central Mixedwood	115,946	26
Lower Foothills	303,992	69
Upper Foothills	21,161	5
TOTAL	**441,099**	**100**

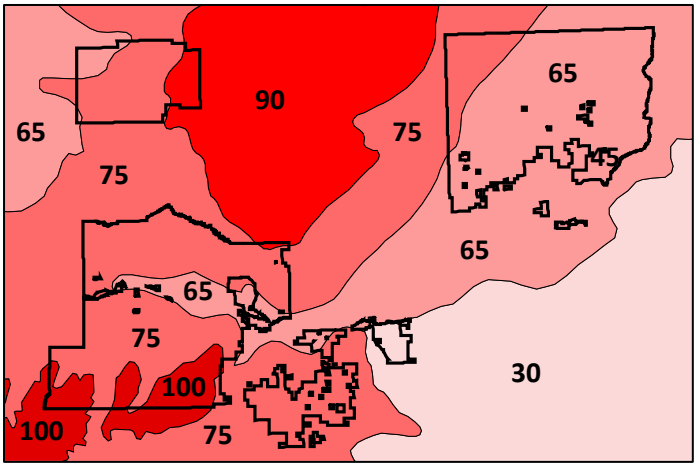
Considering that the Upper Foothills accounts for only 5% of the study area, and is ecotonal, the range of ecological conditions across the Millar Western FMA area is fairly consistent. Most of the topography is level to gently rolling, the climate involves short summers and long, cold snowy winters, and the vegetation is largely a mix of aspen, poplar, birch, and pine with occasional pockets of black spruce fens and bogs (Table 2).

Table 2. Summary of biotic and abiotic conditions across the study area.

Natural Region	Natural Subregion	Elevation	Topography	Climate	Vegetation	Soils	Growing Degree Days >5^{0}C	Mean annual Precip (mm)	Relative Summer Moisture Index
Foothills	Upper Foothills	950-1750m	Rolling to steeply sloped	Short wet summers, snowy cool winters	Dense Pl forest (low el) to dense Sb, Sw forest (high el). Small area in wetlands.	Luvisols, with some brunisols	900	650	2
	Lower Foothills	650-1625m	Gently rolling with plateaus	Short summers with average precip, colder very snowy winters	Highly variable. Mostly mesic dense mixedwood forest (At, Pl, Sw, Pb, Ta, Fir, shrubs). Very little water or wetlands	Luvisols, with some brunisols	1,100	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	1,240	480	3.8

Estimates of the average pre-historical long-term fire cycle range from 30–100 years across the study area, although the vast majority is 65–75 years (Figure 2, from Andison 2019).

Figure 2. Long-term-fire-cycles for the study area in years (From Andison 2019).



5.0 Methods: Choosing a Spatial Model

D.W. Andison

By definition, models are simple, incomplete representations of reality (Hammah and Curran 2009). There is also a key trade-off between complex models and simple ones. The "best" model is not necessarily the most complex or realistic one, but rather the model that best suits the purpose. The rule of parsimony 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, modelling objectives were very simple and general in nature; to define the natural, pre-industrial range of a) seral-stage levels and b) patch sizes by broad vegetation types, and broad geographic zones. This requires a model with the following attributes:

1. Fully spatial,
2. Fully stochastic,
3. Able to function at multiple scales,
4. Very good at capturing known fire patterns,
5. Able to accurately measure /represent known disturbance regime parameters (mostly frequency, size, and severity),
6. Able to generate results in a timely manner, and
7. Work at massive spatial scales (i.e., over 100 million ha).

These requirements were quite restrictive, and narrowed our options considerably since it meant the model must be a) raster-based at a scale of no larger than 10 ha, b) able to function across multiple fire regimes, c) able to handle and integrate multiple spatial data sources, and d) highly efficient in terms of language, memory and processing capacity.

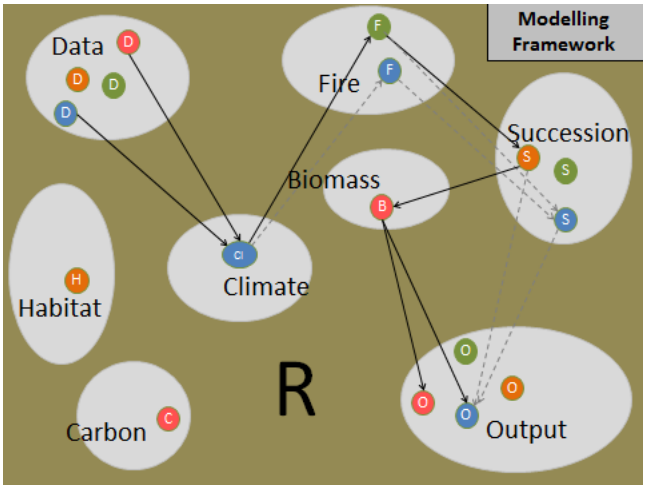
At the outset of this project, there was no existing model that met all of these requirements. However, several were close enough that they could have been adapted with some effort (i.e., Landis, Bfolds, Landmine, Alces, and SELES). As part of the process for this project, the pros and cons of each model were researched and summarized, the likely costs associated with adapting each to suit the new parameters calculated with the help of local experts, and the risks of each not achieving the desired outcomes and objectives identified (e.g., what were the chances that scaling up model X to 100 million ha and adding component Y would even run on a computer, let alone produce output in a timely manner?). The cost and time estimates to upgrade any of the existing model options were considerable.

Another option presented itself at the same time. A CFS-Laval academic partnership (Drs. McIntire and Cumming respectively) were fleshing out the architecture of, and starting to write code for, an ensemble modelling framework called SpaDES (Spatially Discreet Event Simulator). Ensemble models are not models *per se*, but rather frameworks within which multiple models, and/or model components (i.e., modules) can interact (Krueger et al. 2012). In this case, the idea was to create a universal scheduling environment in R that would allow model modules (even ones from existing models) to communicate

and be interchangeable. For example, in Figure 3, there are four different spatial data modules, two fire spread modules, and three forest succession modules to choose from (see below).

Thus, the alternative to investing in upgrading an existing model was to invest in the development of a new, potentially far more powerful modelling framework that is SpaDES, within which a specific module configuration would be developed to achieve the goals of this project.

Figure 3. The SpaDES environment (brown shaded area) allows various modules to communicate and even be exchanged for other, parallel modules. The black lines represent one possible configuration of modules — out of dozens.



There were several benefits of going with the SpaDES option. First, by design, the final product would be open source. This means the final product can be used, modified and shared openly and free of charge to anyone — as opposed to proprietary software, which is not only unavailable for independent review, but must be purchased. Second, because LandWeb would be associated with a larger, open source product it also creates a legacy. LandWeb partners are thus able to use the model for future, and different research and forecasting needs, as opposed to a one-off static model. Thus, the investment in the objectives of LandWeb could result in payoffs in terms of access to, and use of, a universal spatial model for multiple purposes. Third, the plan for LandWeb in SpaDES was to create a stand-alone app available (free of charge) online to anyone. Finally, the various modules necessary to fulfill the objectives of this project would be adapted from existing, proven models, as opposed to writing new modules from scratch.

The greatest risk of going with the SpaDES option was the unknown amount of time and effort required to not only design, build, test, and validate a new modelling framework, but to be the first to attempt to build a specific configuration and app within that framework. Writing, validating and error-checking code is notoriously challenging and time-consuming, and in this case there was no shortage of technical challenges to potentially overcome. So, although the original time and cost estimates from the modelling team were well within the timelines of the project, the resources to complete a LandWeb configuration within SpaDES could well have been significantly greater than we had. In the worst case scenario, resources would be depleted before the end of the project, and with no results to show for the effort. On the other hand, this same risk also existed for the existing model upgrade option. For example, model architecture aside, the sheer effort required to acquire, compile, validate, overlay, and access the massive spatial databases required is without precedent.

In the end, the HL Program Lead chose to support the work of the SpaDES modelling team to develop a needs-specific, LandWeb configuration.

6.0 Methods: LandWeb and SpaDES

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6.1 LandWeb Study area

The study area for LandWeb includes the western-most 125 million ha of the Canadian boreal forest extending west from the Rocky Mountains to beyond the Manitoba border to the east, and from the southern boundary of the forest-grassland interface approximately to the 62nd parallel into the Northwest Territory. The area includes 73 million ha of Boreal Plain, 25 million ha of Taiga Plain, 20 million ha of Boreal Shield, and 7 million ha of transitional areas of Prairie, Montane Cordillera, Taiga Shield and Boreal Cordillera (Wilken 1986) (Figure 4).

The study area also includes several woodland caribou ranges (Figure 5). Note also that the area that was modelled extends well beyond the boundary of the study area. This is to avoid bias associated with edge effects, and common practice for spatial modelling (Figure 5).

Figure 4. Map of the LandWeb study area ecozones.

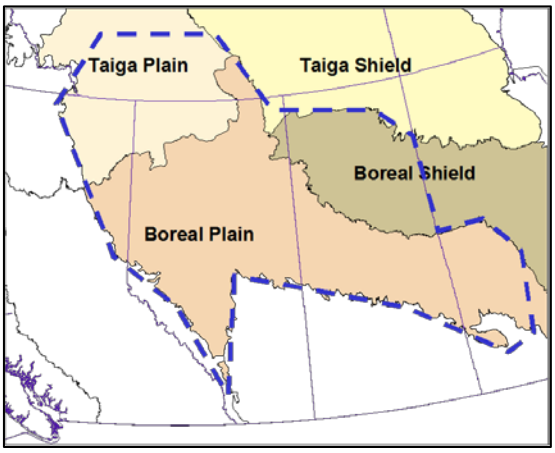
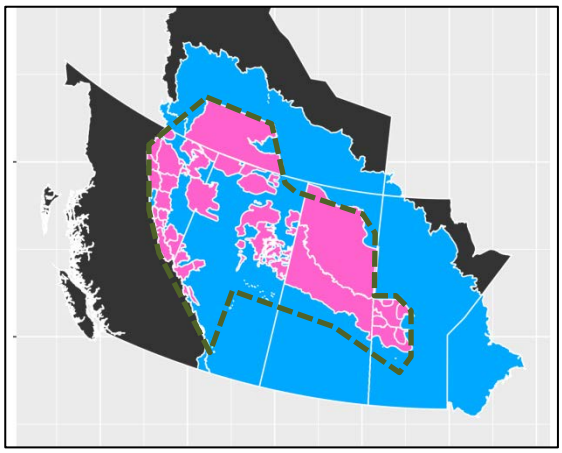


Figure 5. Map of the LandWeb Study Area showing the modelling area (blue) and current caribou range (pink).



6.2 SpaDES

SpaDES is collection of packages for the R Statistical and Data Language used to develop and run spatially explicit simulation model (Chubaty and McIntire 2018; Chubaty 2019a; b; McIntire and Chubaty 2019)). There are three key features of the SpaDES platform that make it an excellent choice for the implementation of the LandWeb model. The first is that SpaDES leverages the availability in R of a vast number of robust scientific computing and data visualization packages. Second, using R for data preparation, analysis, *and simulation*, provides a streamlined data-model pipeline and workflow. Finally, SpaDES is built with the explicit notion of model components that are interchangeable and easily

updatable (i.e., modular). In this sense, SpaDES simply schedules and run various model components (i.e., modules).

Although individual modules are designed to be standalone units, their design includes several features that facilitate use with other modules (i.e., module integration). Each module includes metadata that define its parameter values, as well as data inputs and outputs. These data dependencies are used by SpaDES to calculate module interconnectedness *via* the data objects shared among modules. The specific collection of modules (with their parameterizations and data dependencies) used by LandWeb (i.e., configuration) incorporate and build on models developed for and reusable in other research contexts. We describe each module used in LandWeb simulations in more detail below.

6.3 Data Sources

Data used for the model are derived from multiple sources, and include both open (and freely available) data as well as proprietary partner-supplied data. Data sources for each module are identified in the module descriptions below (Table 3).

Table 3. Summary of spatial data sources used

Data product	Source URL
Pickell land cover and forest inventory data (Pickell and Coops 2016)	N/A
"kNN data" (Beaudoin et al. 2014)	http://tree.pfc.forestry.ca/
LCC2005 v1.4 (Latifovic and Pouliot 2005)	ftp://ftp.ccrs.nrcan.gc.ca/ad/NLCCLandCover/LandcoverCanada2005_250m/LandCoverOfCanada2005_V1_4.zip
Forest Resource Inventory (LandWeb partners, prepared by Silvacom)	N/A
CASFRI v4 (2016) (described in Cosco 2011)	N/A

6.4 Model Code

All modules are written in R and all model code was developed collaboratively using GitHub (https://github.com), with each module contained in its own (private) git repository (Table 4). Code that is shared among modules was bundled into R packages, and hosted in open git repositories. All package code is automatically and regularly tested using cross-platform continuous integration frameworks to ensure the code is reliable and free of errors.

Table 4. Module and package code repositories used for the LandWeb project. Module code repositories are currently private; package code repositories are open.

Code Repository	Description	URL
Modules		
LandMine	A reimplementation of Andison's fire model, simulating fire ignition and spread.	https://github.com/PredictiveEcology/LandMine
LandR Biomass_speciesData	Prepares species input layers from multiple data sources.	https://github.com/PredictiveEcology/Biomass_speciesData
LandR Biomass_core	Simulates vegetation growth, mortality, aging, and dispersal. Updates biomass following other modules' events, and produces summary figures and tables.	https://github.com/PredictiveEcology/Biomass_core
LandR Biomass_regeneration	Simulates post-disturbance (e.g. fire) biomass regeneration.	https://github.com/PredictiveEcology/Biomass_regeneration
LandR Biomass_borealDataPrep	Prepares multiple data objects used by Biomass_core; customized for Canadian Boreal Forests.	https://github.com/PredictiveEcologyeliotmcintire/Biomass_borealDataPrep
LandWeb_output	Summarizes and prepares model outputs specifically for the LandWeb project.	https://github.com/fRI-Research/LandWeb_output
LandWeb_preamble	Creates study areas, including all FMA polygons, and prepares inputs for the main LandWeb simulation.	https://github.com/fRI-Research/LandWeb_preamble
timeSinceFire	Keeps track of forest pixel ages during the simulation.	https://github.com/fRI-Research/timeSinceFire
Packages		
LandR	Landscape Ecosystem Modelling in R	https://github.com/PredictiveEcology/LandR
LandWebUtils	Additional utilities for LandWeb analyses	https://github.com/PredictiveEcology/LandWebUtils
map	Defines a meta class of geographical objects, the 'map' class, which is a collection of map objects (sp, raster, sf), with a number of metadata additions to enable powerful methods (e.g., for leaflet, reproducible GIS, etc.)	https://github.com/PredictiveEcology/map
pemisc	Miscellaneous utilities developed by the Predictive Ecology Lab Group	https://github.com/PredictiveEcology/pemisc

6.5 LandWeb simulation model

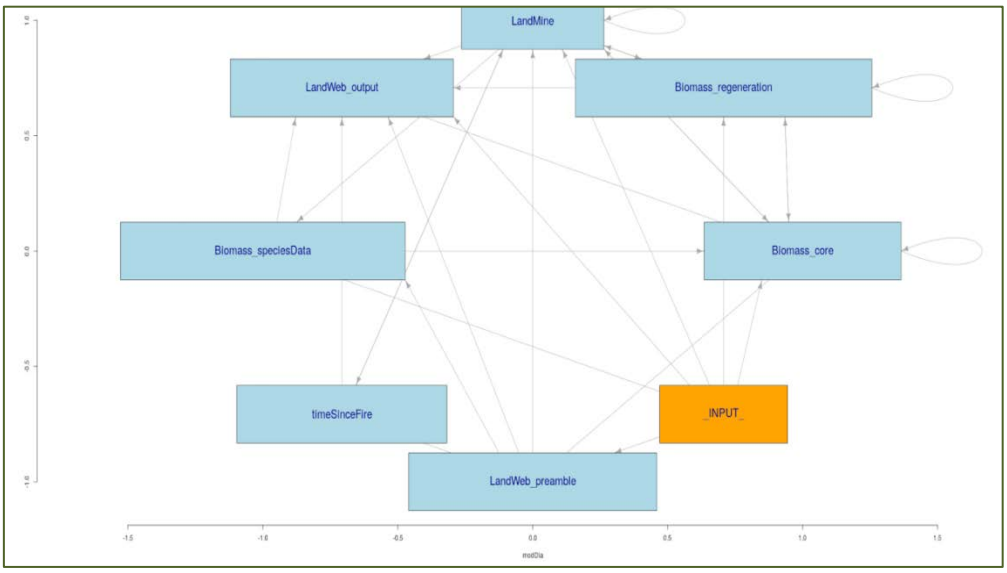
6.5.1 Overview

To our knowledge, LandWeb is the first large scale, data-driven approach to simulating historical NRV. In developing the model, analyses, as well as the infrastructure to host data, we strived to implement a single, reproducible workflow to facilitate running simulations, analyses, model reuse and future expansion. This tight linkage between data and simulation model was made possible *via* its implementation using the SpaDES[1] family of packages (Chubaty and McIntire 2018; Chubaty 2019a; b) within the R Statistical Language and Environment (R Core Team 2018). SpaDES facilitates the development of large-scale spatial simulation models.

[1] Packages used includes, SpaDES, SpaDES.core, SpaDES.tools, reproducible, quickPlot, LandR, LandWebUtils, amc, pemisc, map, raster, sp, sf, and data.table

The LandWeb model integrates two well-used models for forest stand succession and fire simulation, implemented in the SpaDES simulation platform as a collection of sub-models implement as SpaDES modules. Each of these modules are generally categorized by their primary purpose, summarized in Figure 6 and are further described below.

Figure 6. Schematic diagram of the modules within the LandWeb model.



Data preparation. Simulations were run for the entire LandWeb study area, which spans most of the western Canadian boreal forest. Input data were derived from several publicly available, remote-sensed datasets (Beaudoin et al. 2014), as well as proprietary data compiled by Pickell and Coops (2016).

Vegetation dynamics were modeled using a re-implementation of the LANDIS-II Biomass model; a widely used and well-documented dynamic vegetation succession model (Scheller et al. 2007; Scheller and Mladenoff 2004; 2007). Our re-implemented model largely follows the original LANDIS-II source code (v 3.6.2), but with some modifications.

Fire dynamics were modeled using a re-implementation of the fire sub-model of Andison's (1996; 1998) Landmine model of landscape disturbance.

Summary maps and statistics were produced/calculated from simulation outputs, and consist of maps showing the time since fire as well as histogram summaries of 1) number and/or total area of large patches (i.e., patches above the number of hectares specified by the user) contained within the selected spatial area, and 2) the vegetation cover within the selected spatial area. Histograms are provided for each spatial area by polygon, age class, and species. Authorized users can additionally overlay current stand conditions onto these histograms. Simulation outputs were summarized for several publicly available reporting polygons (including Alberta Natural Ecoregions and woodland caribou ranges).

6.5.2 Data preparation

The following describe the modules used for LandWeb.

6.5.2.1 LandWeb_preamble Module

This module performs several GIS data preparation steps to 1) define the study area for LandWeb, and 2) to ensure that all downstream geospatial objects are converted to use the same geospatial geometries (e.g., projection, extent, resolution). Furthermore, this module implements several automated methods for ensuring the validity and the compatibility of input data layers with the downstream simulation components. In particular, it removes non-tree pixels form the Land Cover Classification 2005 and Forest Resource Inventory data sets, and overlays these inventory data into individual forest inventory (by species) and land cover layers (Table 5).

The module defaults to processing cover data for five species/genera: fir (*Abies spp*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), pine (*Pinus sp*p), and trembling aspen (*Populus tremuloides*).

Table 5. Data sources used by LandWeb_preamble module

Forest Cover Layer(s)	Source URL
Pickell land cover and forest inventory data (Pickell and Coops 2016)	N/A
"kNN data" (Beaudoin et al. 2014)	http://tree.pfc.forestry.ca/
LCC2005 v1.4 (Latifovic and Pouliot 2005)	ftp://ftp.ccrs.nrcan.gc.ca/ad/NLCCLandCover/LandcoverCanada2005_250m/LandCoverOfCanada2005_V1_4.zip
Forest Resource Inventory and Land Cover data (LandWeb partners, prepared by a.k.a. "Current Conditions" data	N/A
CASFRI v4 (2016); described in (Cosco 2011)	N/A

6.5.2.2 Biomass_speciesData Module

This module downloads and extracts several species cover data layers (Table 5) and overlays them to produce single cover layers by species. It also performs several data pre-processing steps to ensure that 1) all data use the same geospatial geometries, 2) data are cropped to the study area, and 3) attempts to correct or fill-in any inconsistent or missing data are based on data from other layers. The details of how the layers used in this module were initially developed are reported in their respective reports and publications cited above (Table 5).

As above, this module defaults to processing cover data for five species/genera: fir (*Abies spp*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), pine (*Pinus sp*p), and trembling aspen (*Populus tremuloides*).

6.5.2.3 Biomass_borealDataPrep Module

This module converted open datasets that were available for all of Canada's forests into the input requirements for Biomass_core, a forest landscape succession model derived from the Landis-II Biomass Succession Model (Scheller et al. 2007; Scheller and Mladenoff 2004). It was primarily used to estimate vegetation growth parameters including maximum biomass, maximum aboveground net primary

productivity (aNPP), and seedling establishment probability, and to simulate the tree cohorts necessary for Biomass core. This module also provided other parameters, such as species tolerances to shade, and other plant traits (e.g., longevity, ability to re-sprout, etc.). These traits are the same as those derived from LANDIS-II, though the specific values used in the LandWeb simulations were 1) selected to produce relative species abundances that resemble the initial conditions data (Table 6), and 2) others were determined using linear mixed effects models fit to the LandWeb study area (described below).

The module makes use of many datasets from the National Forest Inventory, including aboveground biomass, stand age, and species cover (Beaudoin et al. 2014) as well as the 2005 National Land Cover of Canada (Latifovic and Pouliot 2005) and the Ecological Land Classification of Canada (LCC) (Statistics Canada 2018) (Table 7).

Table 6. Species traits values modified from LANDIS-II for LandWeb.

Species	Abie_sp	Pice_gla	Pice_mar	Pinu_sp	Popu_sp
Area	BSW	BP	BP	BP	BP
longevity	200	400	250	150	140
sexualmature	20	30	30	15	20
shadetolerance	3	2	3	1	1
firetolerance	1	2	2	2	1
seeddistance_eff	250	100	320	300	500
seeddistance_max	1250	1250	1250	3000	3000
resproutprob	1	1	1	1	1
resproutage_min	0	0	0	0	0
resproutage_max	400	400	400	400	400
postfireregen	resprout	resprout	resprout	resprout	resprout
leaflongevity	2	3	3	2	1
wooddecayrate	0.02	0.02	0.02	0.01	0.07
mortalityshape	15	15	15	15	25
growthcurve	0	1	1	0	0
leafLignin	0.2	0.2	0.2	0.2	0.1
hardsoft	soft	soft	soft	soft	hard

Table 7. Data sources used by Biomass borealDataPrep module.

Data Source	URL
Land cover and forest inventory data (Pickell and Coops 2016)	N/A
"kNN data" (Beaudoin et al. 2014)	http://tree.pfc.forestry.ca/
LCC2005 v1.4 (Latifovic and Pouliot 2005)	ftp://ftp.ccrs.nrcan.gc.ca/ad/NLCCLandCover/LandcoverCanada2005_250m/LandCoverOfCanada2005_V1_4.zip
Forest Resource Inventory and Land Cover data (LandWeb partners, prepared by Silvacom; 2016) a.k.a. "Current Conditions" data	N/A
CASFRI v4 (2016); described in (Cosco 2011)	N/A
Initial communities (Landis-II)	https://github.com/LANDIS-II-Foundation/Extensions-Succession-Archive/master/biomass-succession-archive/trunk/tests/v6.0-2.0/
Species traits (Landis-II)	https://github.com/dcyr/LANDIS-II_IA_generalUseFiles

A number of data cleaning operations were used to treat pixels with problematic sample sizes and logical inconsistencies. First, land cover classes (LCC) corresponding to recent burns, old burns, and cities were reclassified by searching the focal neighbourhood and using adjacent cover classes. These pixels were omitted from the subsequent fitting of statistical models, but were assigned predicted values from these models. Other situations arose where cover was 10% but biomass was zero, or biomass was 25 tons/ha but age was zero.

In these instances, tree species occupying fewer than 5 pixels (< 1 ha) were removed. Both age and biomass required fidelity to species cover, since cover was presumed to be the most accurately estimated variable. Species-specific above-ground biomass (AGB) was estimated for each tree species present in a given pixel by multiplying the relative cover of the tree by the total AGB of the pixel (this method assumed all tree species had identical cover/biomass relationships). Stand age also had to be corrected with respect to species longevity parameters. This was achieved by fitting a statistical model relating "correct" age observations (i.e., those already corrected for zero cover and with age estimates not exceeding longevity) against the interaction of observed biomass (totalB), species (speciesCode) and percent cover (cover), accounting for the random effect of combination of ecodistrict and LCC (ecoregionCode):

$$age \sim totalB * speciesCode + cover + (1 \mid ecoregionCode) \text{ [Eq. 1]}$$

R^2 marginal = 0.38, R^2 conditional = 0.45

Predicted ages were subsequently bounded to zero on the lower limit. Parameters maxB and aNPP were then estimated from a linear mixed effects model reflecting the response of species-specific biomass (B) to the interaction between age (on the log scale, logAge) and species and % cover and species, accounting for the random effect of ecoregionGroup on the calculated slopes (per species) and intercepts:

$$B \sim logAge * speciesCode + cover * speciesCode + (logAge + cover + speciesCode \mid ecoregionGroup) \text{[Eq. 2]}$$

The maximum aNPP was derived from the formula maximum aNPP = maximum AGB / 30, similar to LANDIS-II. Estimates of Species Establishment Priority were based on a generalized linear mixed effects model relating percent cover and species, accounting for the random effect of ecoregionGroup on the intercepts. In this case, species percent cover was treated as the number of times a species was observed (no. of pixels with cover > 0) per ecoregionGroup, thus following a binomial distribution that was accounted for in the model with a logit link function:

$$logit(\pi) \sim speciesCode + (1 \mid ecoregionGroup) \text{ [Eq. 3]}$$

where π is the probability of finding a species (cover > 0) in an ecoregionGroup, or the proportion of pixels that it occupied.

For both models, coefficients were estimated by maximum likelihood and model fit was calculated as the proportion of explained variance explained by fixed effects only (marginal R^2) and by the entire model (conditional R^2). For the biomass model (Eq. 2), marginal and conditional R^2 were 0.52 and 0.79, respectively; for the percent cover model (Eq. 3), they were 0.07 and 0.13. To estimate maxB we predicted biomass for unique combinations of species and ecoregion code assuming maximum age (i.e., longevity) and maximum cover (100%).

Parameters for the 'Recent burn' and 'Urban' LCC were input from the ecodistrict and LCC of neighbouring pixels using a focal window that iteratively expanded until a valid ecodistrict/LCC was returned.

One of the advantages of this module (and of using SpaDES/R more generally), is that the parameters used for the vegetation succession modules could also be directly estimated from data within the context of the simulation. This is achieved "automatically" should the data or study area change. As with any model, this means that model predictions need to be calibrated every time the study area changes.

6.5.2.4 Vegetation model (LandR Biomass) Module

LandR Biomass is a dynamic landscape vegetation model. As such, it simulated landscape-scale forest dynamics in a spatio-temporally explicit manner, using cohorts of tree species within each pixel. Multiple ecological processes were captured by the model, including vegetation growth, mortality, seed dispersal, and post-disturbance regeneration. These dynamics followed those of the LANDIS-II Biomass Succession module v3.2.1 (Scheller and Mladenoff 2004; Scheller and Miranda 2015), but were modified to improve general utility and computational performance (Barros et al. in prep). In brief, the LandR modules reproduced forest biomass dynamics in a spatially explicit manner at the landscape scale. They simulated biomass changes by cohort (species-age combinations) as a function of age, between-cohort competition for light resources, seed dispersal, germination, and regeneration following a disturbance, and background or fire-related mortality.

6.5.2.5 Biomass_core Module

This module provided the core vegetation dynamics; simulating vegetation growth and mortality processes. The functions that determine growth and mortality were unchanged from LANDIS-II. Growth and mortality dynamics were simulated in biomass units (g/m^2) for each cohort within a stand at an annual time step, regardless of the successional time step used for other processes, such as dispersal or regeneration. Growth was dependent upon the maximum annual primary productivity of a species, cohort age, and competition. Species-specific growth curves dictated the maximum growth for a cohort as it aged. Young cohorts had lower maximum growth, as small trees were not as productive as large, mature trees. Competition acted to reduce growth by limiting the available growing space, while recent disturbances (i.e., from the previous year) increased the available growing space. Competition occurred when a stand contained more than one species-age cohort.

Mortality was derived from two sources, senescence (age-related mortality) and development-related mortality due to the ongoing loss of individual trees and branches from a cohort (Scheller and Mladenoff, 2004). Mortality was dependent upon the living biomass of a cohort, while development-related mortality could not exceed aNPP. As cohorts near their longevity age, age-related mortality increased exponentially, eventually reaching the entirety of the cohort's biomass at the maximum lifespan of the cohort species. Age-related mortality was determined by pre-defined mortality curves that vary by species.

6.5.2.6 Biomass_regeneration Module

This module simulated post-disturbance (in this case fire) regeneration, assuming fires were stand-replacing. In each burnt pixel, the module reset pixel biomass to zero and activated post-fire re-sprouting and/or serotiny depending on species' abilities to re-sprout, their seed establishment probabilities (SEP) in that pixel (i.e., the pixel's ecodistrict and land-cover classes), and their tolerance to shading conditions (which, in this case is zero given all biomass was totally removed after fire) (see Table 8 for species trait values). The module algorithm first determined for which species serotiny would be activated according to shading and SEP (light-loving species and higher SEP increased the probability of serotiny being activated). It then assessed which species rely on re-sprouting and will do so depending on their re-sprouting age limits, shading and re-sprouting probability (i.e., light-loving species and higher re-sprouting probability increased the probability of re-sprouting). For any given pixel, re-sprouting was limited to species that rely on re-sprouting for which serotiny was not activated. This provided an advantage to serotinous species that would otherwise be out-competed by species that rely on re-sprouting.

Table 8. Mean parameter values (and SE) for all geographically varying species inputs and map regions.

Species	Species Establishment	Maximum ANPP	Maximum Biomass
BETU.PAP	0.78 (0.09)	478.76 (77.77)	3,655.17 (694.24)
LARI.LAR	0.60 (0.17)	260.48 (228.97)	1,004.48 (849.30)
PICE.GLA	0.68 (0.02)	929.87 (154.36)	10,559.91 (2,163.76)
PICE.MAR	0.37 (0.15)	551.85 (367.85)	3,816.86 (2,668.30)
PINU.BAN	0.78 (0.06)	1,129.29 (201.95)	12,177.80 (1,088.17)
POPU.BAL	0.82 (0.03)	988.64 (177.21)	7,843.75 (1,254.53)
POPU.TRE	0.82 (0.03)	988.64 (177.21)	7,843.75 (1,254.53)

Having insufficient data to draw from, we assumed that the overall proportion of each species in the landscape doesn't change much over the course of the simulation. Our previous simulation runs showed that stand regeneration — using the LANDIS-II defaults when coupled with the fire dynamics (described below) — was inadequate to ensure that the proportion of each species across the entire landscape remained consistent with current condition data. Rather than re-engineer the underlying LANDIS-II approach to simulating these dynamics, we instead focussed on re-parameterizing the species traits that underlie these dynamics. In particular, we increased dispersal distances and regeneration rates for all species to ensure recolonization of burned pixels, resulting in a *de facto* state-transition model formulation, used successfully in ecological simulations.

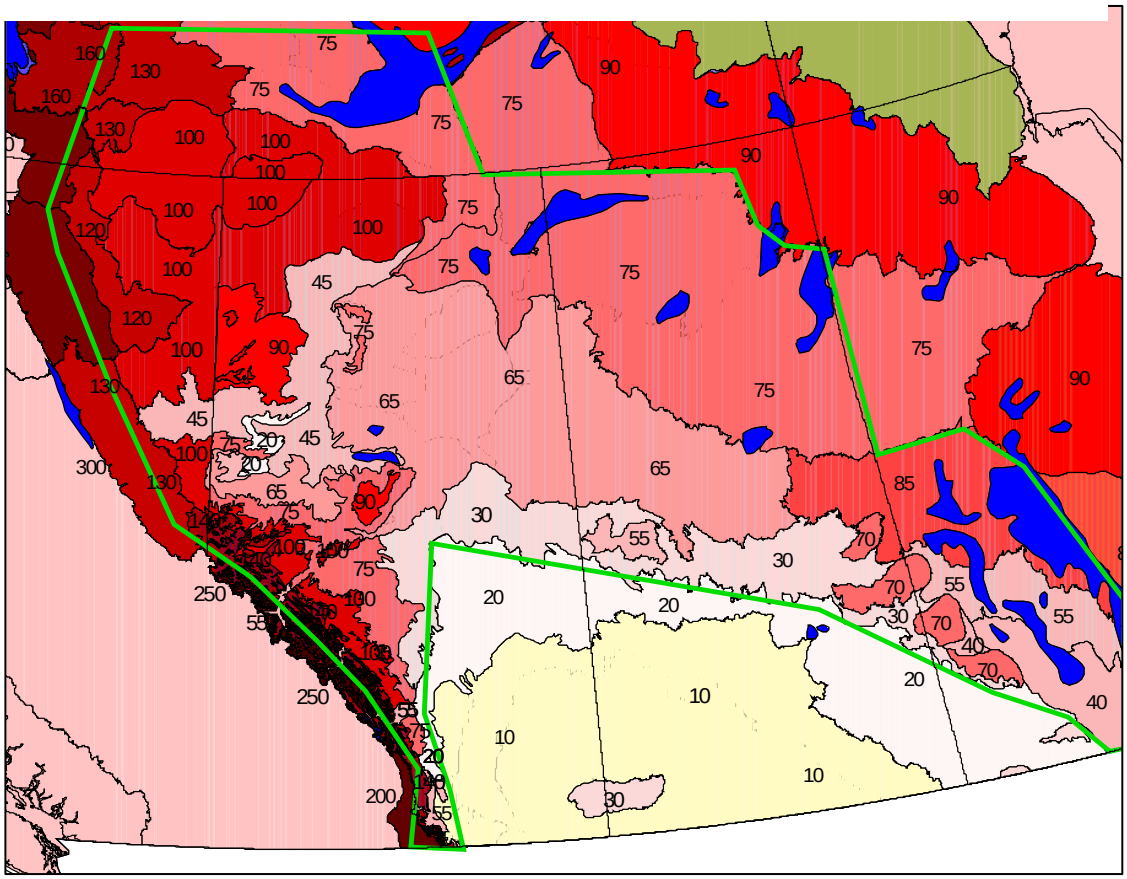
6.5.2.7 Fire model Module

The LandR model has been designed to handle any number of generic disturbance events by accepting a disturbance layer and removing vegetation in those pixels. LandWeb considers fire as the only source of disturbance, as historically, fire is the dominant disturbance agent in boreal ecosystems.

LandWeb uses the fire initiation and spread module from the Landmine model. Landmine is a Monte Carlo based, spatially-explicit simulation model created for predicting the NRV for landscapes in the boreal forest (Andison 1996; 1998; Clarke et al. 1994), and has been widely used in various contexts both in the public and private sectors. It takes as an input a map of the Long-Term Fire Cycles (LTFC;

Figure 7) (Andison 2019) and simulates fire ignition and spread, and can be used to generate maps of forest disturbance (i.e., removes vegetation it burns). The LTFCs are used as fire return intervals in the simulations (Table 9).

Figure 7. Map of long-term fire cycles (in years) for the LandWeb study area (from Andison 2019).



For the LandWeb project, we re-implemented Landmine as a SpaDES module, with some modifications. Ignition is randomly assigned with a general area defined by fire return interval. Once a fire starts in a pixel its spread is affected by the vegetation type of neighbouring pixels (e.g., less likely to move into aspen). It "snakes" around searching neighbourhood for burnable pixels until it reaches its assigned fire size. If it gets stuck, it "jumps" to nearby pixels after a maximum number of tries. All burned pixels have their vegetation removed (i.e., all cohorts removed). The LandWeb implementation of Landmine differs slightly from the original in two ways: 1) fire sizes were drawn from a Truncated Pareto distribution (instead of a negative exponential), and 2) other parameters have not been fitted to the landscapes that are under study in the LandWeb project.

Table 9. Data sources used by Landmine fire module.

Data product	Source URL
Fire cycle map v6 (Andison 2019)	N/A (fix)

We tracked proportion of area burned and compared against the area that was supposed to burn each year, noting that in the current version, we under-burn in many instances due to fires reaching the maximum number of "jumps" permitted. In other words, some fires simply cannot continue spreading/growing due to spatial restrictions imposed by neighbouring pixels that have inflammable cover classes or have already been burned. Even when only underburning by 1–2%, the area burned dictated by the fire return interval (LTFC) map is not achieved. Despite this, our earlier simulations showed very high disturbance causing excessive removal, coupled with insufficient regeneration of burned pixels. As mentioned above, these interactions required re-parameterization of the species traits to ensure sufficient regeneration post-fire.

6.5.2.8 LandWeb_output Module

This module produces raster maps of the leading vegetation types, as well as calculating the average time since fire over the course of the simulation.

6.5.2.9 timeSinceFire Module

This module updates the pixel-level stand age (i.e., time since fire), by incrementing the age of unburned pixels, and resetting the ages of burned pixels to 0. It also produces raster maps of time since fire as outputs.

6.5.2.10 Post-processing

Outputs from all simulation reps were used to calculate and report the NRV metrics identified by the partners, and generate custom maps for specific geographic areas (i.e., reporting polygons) within the study area. The collection of reporting polygons used in model post-processing reflects the principal considerations of forest managers and provincial government scientists, and can be classified into two main categories. First, there are reporting polygons corresponding to administrative boundaries such as provincial, park, and FMA boundaries. Second, there are reporting polygons that correspond to ecological boundaries such as ecological zones and caribou ranges. See Table 10 for a summary of reporting polygons used.

Table 10. Summary of reporting polygons used in presenting LandWeb simulation model results.

Reporting polygon	Source URL
Administrative boundaries	
Provincial boundaries	https://biogeo.ucdavis.edu/data/gadm3.6/Rsp/gadm36_CAN_0_sp.rds https://biogeo.ucdavis.edu/data/gadm3.6/Rsp/gadm36_CAN_1_sp.rds
Parks boundaries	https://www.altalis.com/map:id=117
FMA area boundaries (2015)	https://www.albertaparks.ca/albertaparksca/library/downloadable-data-sets/
Ecological boundaries	
Ecological Land Classifications (Statistics Canada 2018)	http://sis.agr.gc.ca/cansis/nsdb/ecostrat/district/ecodistrict_shp.zip http://sis.agr.gc.ca/cansis/nsdb/ecostrat/region/ecoregion_shp.zip http://sis.agr.gc.ca/cansis/nsdb/ecostrat/zone/ecozone_shp.zip
Alberta Natural Subregions (2005)	https://www.albertaparks.ca/media/429607/natural_regions_subregions_of_alberta.zip
Boreal Caribou Ranges (Environment Canada 2012)	http://data.ec.gc.ca/data/species/protectrestore/boreal-caribou-ranges-in-canada/?lang=en
Alberta Caribou Ranges	https://extranet.gov.ab.ca/srd/geodiscover/srd_pub/LAT/FWDSensitivity/CaribouRange.zip
British Columbia Caribou Ranges	https://catalogue.data.gov.bc.ca/dataset/caribou-herd-locations-for-bc

6.5.3 Running the Model

To ensure sample independence, the model was run for several thousand years, measuring snapshots at every 100 years for a total of 60 snapshots.

6.6 Validation

One of the ultimate measures of confidence in model output is the degree to which it compares to existing knowledge. One of the critical model assumptions imposed at the start of the project was that the existing proportion of vegetation types should reflect the ***average*** proportions from the modelling simulation runs. Although not a perfect assumption, it sufficiently captures reality, notwithstanding climate change impacts. In this case, LandWeb created landscapes that shifted some vegetation types well beyond that which was expected. More specifically, the model was replacing conifer species with pioneer hardwood species and *Abies* at an unrealistic rate.

This suggested one or more model parameters, assumptions, or data inputs were not being accurately represented. This prompted a thorough and lengthy review of code and algorithms, input-data, parameters and other model assumptions. No major "bugs" were found in the code, although several data issues were identified. In the interests of time, the short-term fix was to ask the succession module to maintain (on average) the proportion of vegetation types observed on the landscape today.

After several months of attempting to reconcile this through error checking and manipulating parameters, the solution was to simplify the succession module from a vital attributes architecture (Noble and Slatyer 1980) to emulate a *de facto* state transition model (Stringham et al. 2003). However, this still created some unlikely vegetation type shifts.

There are several possible explanations for this inconsistency between actual and expected results.

1) The assumption that the average pre-industrial landscape conditions reflect current vegetation conditions was in error. Natural dynamics (such as fire frequency and severity) are constantly changing, and the model may in fact be accurately reflecting shifts in species based on the historical input assumptions.
2) The LTFC estimates (used as model inputs) were significantly wrong.
3) The model was under-estimating fire severity in the form of the amount and type of remnant vegetation. As the amount of unburned forest increases within individual fires, the lower the reliance on the youngest cohort to provide seed, and the greater the chances of later successional species such as white spruce to invade.
4) There are still un-discovered errors in the (one or more) model modules.
5) There are missing parameters in (one or more) of the modules that may be relevant.
6) The resolution (i.e., pixel size) of the model was too coarse to capture the scale at which the relevant dynamics (of mortality, forest dynamics, and succession) occur.

7) The succession module was not calibrated to properly reflect the ecological diversity across the larger LandWeb study area.

While some of these possibilities are more likely than others, there are arguments for and against each as follows (mirroring the same numbering reference as above):

1) There is merit to the possibility that vegetation types today do not reflect those of the past. However, the degree to which the model shifted vegetation types was well beyond anything expected.
2) Long-term-fire-cycle is a highly influential model parameter influencing successional dynamics. The frequency and coverage of definitive, empirical studies across the LandWeb study area is highly variable. In an effort to address these gaps, a related but independent research project developed the LTFC map used here as input for the model using a combination of the available empirical evidence. The opinion of a large number of fire regime experts over four years of input was also solicited (Andison 2019). The quality of the evidence varies across the LandWeb study area. While there is little direct evidence of historical fire cycles on the Millar Western FMA area, there are several adjacent pieces of evidence of moderate to high quality.
3) The boreal forest has, for many years, assumed to be a “stand-replacing” ecosystem in which natural disturbances such as wildfire kill all or most of the trees resulting in single-aged forest (Johnson 1992). Most, or all, simulation models (including LandWeb) reflect this perception and a) kill 100% of the vegetation within any cell that is disturbed, and b) do not prioritize residual levels as either an input or output parameter. However, more recent evidence suggests that historical boreal wildfires are a mix of low, moderate and high severity fires (Andison and McCleary 2014). This is relevant to this study because as fire severity decreases, the amount of surviving forest increases, which changes the dynamics of regeneration, competition, and relative growth rates. For example, a fire in which only 20% of the trees survive will look very different than one in which 80% of the trees survive. It will also have very different species attributes as regards regeneration and growth.
4) It is not possible to be completely sure that there are not errors or logical inaccuracies. Case in point is that during the process of translating the succession module from LANDIS, the modelling team found a systematic error — in a model that has been used hundreds of times, with dozens of publications over the last 20+ years. As a reminder, models are representations of reality, and thus always wrong (to some degree). They are also notoriously under-tested against empirical data (Beverly and McLoughlin 2019). We use models because they are useful, not because they are perfect.
5) The possibility of the model not including key parameters is difficult to evaluate, which makes it a constant source of error of unknown influence. Just because a module is mechanistic (i.e., measures actual detailed functions) does not mean that the list of mechanisms is complete or the assumptions in terms of their influence to the output is accurate. In fact, more sophisticated mechanistic models necessitate a significantly higher level of understanding of system processes, and thus a higher level of trust. What is the impact of parameter three (of 20+) on

the outcome? What is the impact of not including parameter X, or getting it "right"? It is easier to be confident that individual model parameters are functioning as expected than it is to be confident that the various parameters fit together to create robust results.

6) One of the ways in which LandWeb is unique is that it attempted to blend fine- with coarse-scale dynamics. For example, the pixel size chosen for LandWeb was 6.25 ha — largely to accommodate computational efficiency. That corresponds to a square box with 250 m per side, and at least 125 m from the pixel centroid. In contrast, seeding distances for white spruce (for example) are 15–30 m. So the dispersal of white spruce seed is partly *within* pixels, and partly *between* pixels. How the model deals with such issues is critical. Similarly, the survival of individual (seed-bearing conifer) trees may not be accurately represented at a scale of 6.25 ha.
7) The succession module was calibrated to represent the entire LandWeb study area. In fact, the climatic, ecological, and wildfire dynamics conditions vary widely. So, while there may be places where the module performs very well, the LandWeb study area may require multiple, unique calibrations.

As important as it is to find the source(s) of the inconsistencies described above, this issue was unlikely to significantly impact the results in this case. Recall that the output metrics were both simple and broad. For example, when all vegetation types are combined (for both seral-stage levels and patch sizes) the results do not differ significantly from the vegetation type results. Thus, the LandWeb output will only marginally affected by this unresolved problem. However, this issue may be more significant if/when the model is used for other purposes where the details of stand type parameters are important (e.g., habitat types, impact of climate change on species shifts, etc.).

7.0 Results

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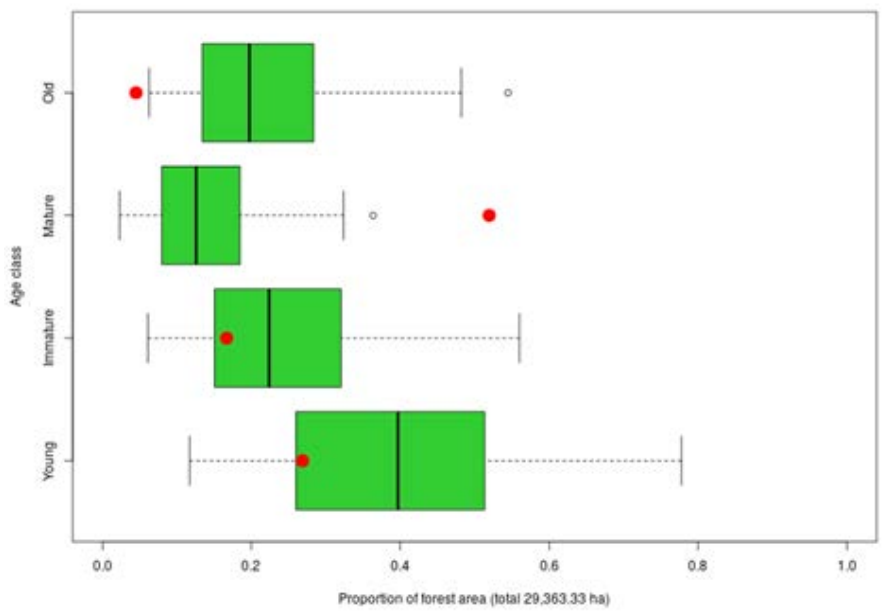
The results presented in this section blend the data from the two FMA pieces. The western piece is not nearly large enough to be calculating NRV metrics, or making comparisons at coarse scales.

7.1 Non-spatial Results

The non-spatial results from the NRV modelling results are presented as *box and whisker plots (Figure 8)*. Box and whisker plots divide dozens, hundreds, or thousands of measurements into four evenly spaced groups (quartiles), each one representing 25% of the total number of measurements. 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. The 50th percentile is the median. In Figure 8, the first quartile is the 'whisker' dotted line on the left, the second quartile is the green box left of the black vertical line (median), the third quartile is the green box on the right, and the fourth quartile is the (dotted line) whisker on the right. Note also in Figure 8 there are small open circles. These are known as *outliers* because they are significantly higher or lower than the rest of the data.

Figure 8. Historical ranges (box plot) and current levels (red dot) of pine forest on a sample study area – just for demonstration.



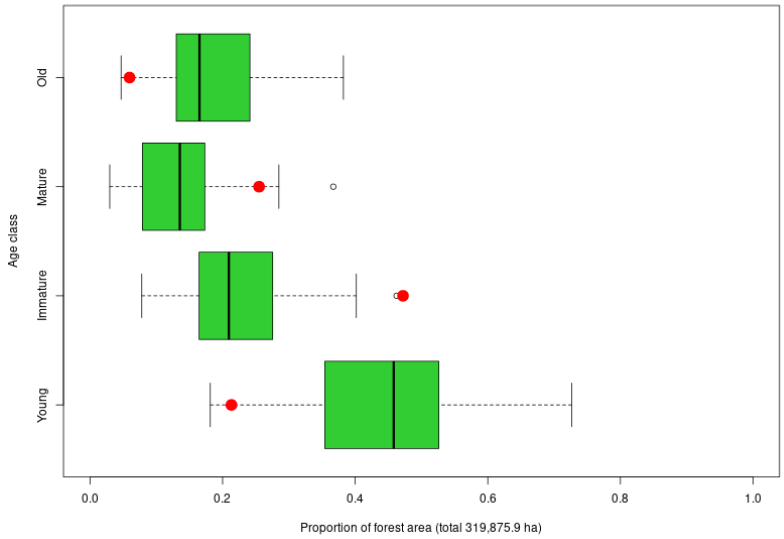
Box and whisker plots not only simplify output into a more visually intuitive form, but also allow simultaneous viewing of all seral stages. For example, each set of four quartiles represents all four seral-stages of a specific vegetation type. The associated area (ha) of the vegetation type is shown in parentheses in the x-axis label. In this case, there were just over 29,000 ha of forest in the area of interest, and every set of data points from every one of the 60 landscape scenes added up to 29,000 ha across the four seral-stages.

Lastly, the red dot in each graph represents the current condition. So in the "old" seral stage in Figure 8, the current condition is below even the minimum level of NRV.

The tables associated with each of the Figures shown in this section are given in Appendix A.

The current seral-stage distribution of all forest types on the study area is unbalanced relative to the NRV data from modelling. Over 73% of the forest in the study area is between 40–120 years of age, which is well beyond the upper NRV threshold (Figure 9). Immature forest levels are particularly high relative to NRV (currently 47%, compared to the maximum observed in the NRV modelling of 40%). In contrast, the current levels of both young and old forest are statistically only just barely within the lower bounds of NRV.

Figure 9. Historical ranges (box plot) and current levels (red dot) of all forest on the Millar Western FMA area.

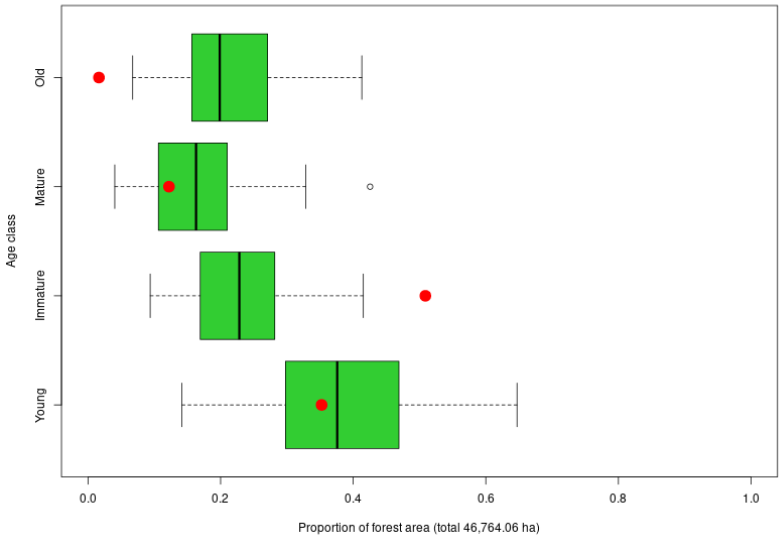


7.1.1 Major Vegetation Types

The following results break down the Millar Western FMA area by five of the six forest types. There was insufficient area in *Abies* forest types to warrant presenting the results.

Current levels of pine do not align well with the NRV modelling data. Current levels of old pine are 2%, which is well below the 13% lower level of NRV, and the 20% NRV median (Figure 10). Mature pine forest is currently 12%, which is on the lower side of, but well within NRV. In contrast, the current amount of forest 40–80 years of age (51%) is well beyond the 42% upper bound of NRV, and more than double the NRV median. The current level of young forest is close to the NRV median (Figure 10).

Figure 10. Historical ranges (box plot) and current levels (red dot) of pine forest on the Millar Western FMA area.



Current levels of black spruce forest show more extreme patterns relative to NRV. Individually, both the mature and immature forest levels are statistically beyond NRV, accounting for an unprecedented 80% of the black spruce forest area (Figure 11). The current old forest level of 7% is only just above the NRV minimum threshold of 5%. The current young forest level of 12% is below the minimum NRV threshold observed of 20%, and well shy of the NRV median of 46% (Figure 11).

Figure 11. Historical ranges (box plot) and current levels (red dot) of black spruce forest on the Millar Western FMA area.

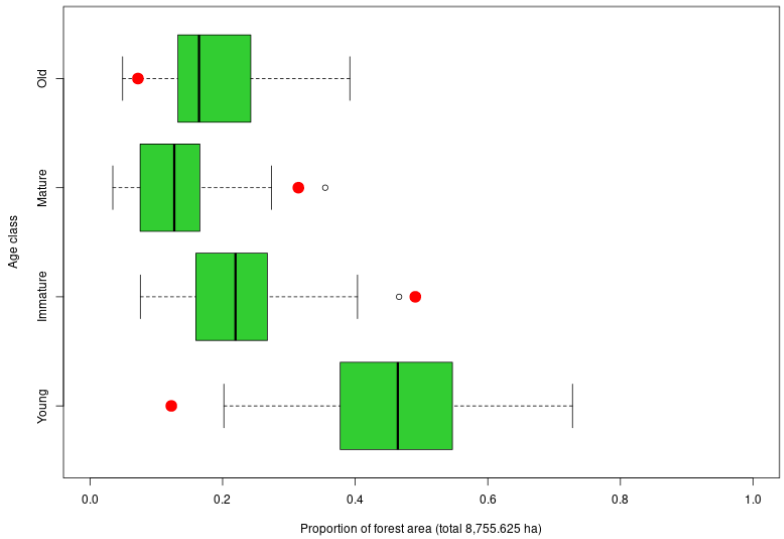
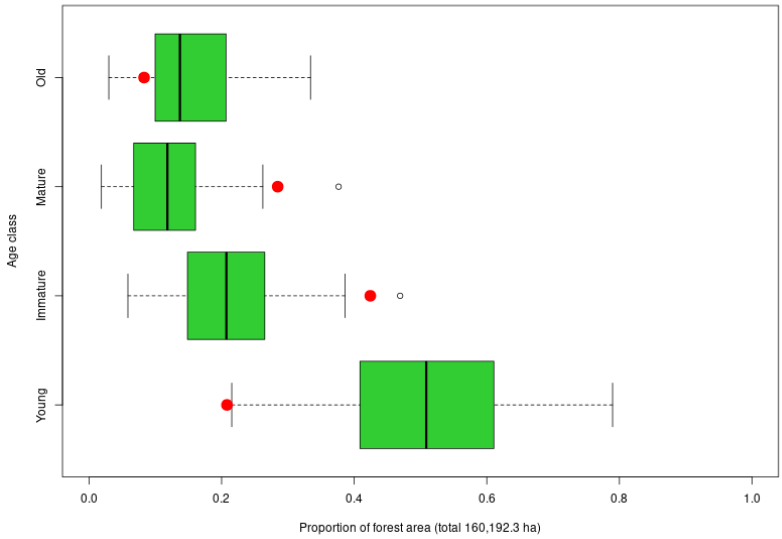


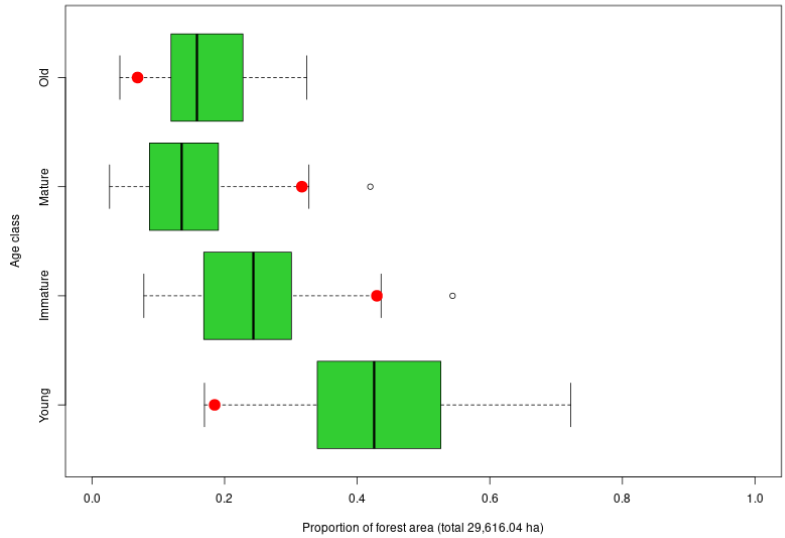
Figure 12. Historical ranges (box plot) and current levels (red dot) of mixedwood forest on the Millar Western FMA area.



Current levels of mixedwood forest were almost entirely beyond NRV but in a similar pattern to that already observed. The current levels of immature and mature forest are both beyond the statistical upper threshold of NRV (Figure 12). When the two are combined, the contrast between current condition and NRV are only magnified. Current young forest levels of 21% are just below the lower NRV threshold. The current 8% old forest levels are within, but at the 10% NRV threshold (Figure 12).

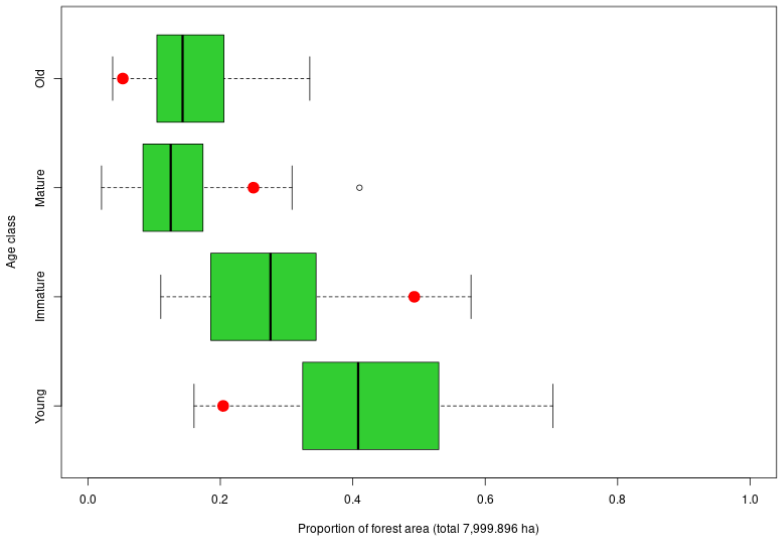
Current young forest (19%) was very close to the lower end of NRV, and well below the historical median of 43% (Figure 13). Current old white spruce levels are within, but at the lower end of NRV. Both immature and mature forest levels of mixedwood are currently at the upper threshold of NRV (Figure 13).

Figure 13. Historical ranges (box plot) and current levels (red dot) of white spruce forest on the Millar Western FMA area.



Old and young deciduous forest levels are both close to the statistical lower boundary of NRV. The vast majority (74%) of the current deciduous forest on the study area is immature and mature (i.e., 40–120 years of age), which is well beyond the NRV upper boundary.

Figure 14. Historical ranges (box plot) and current levels (red dot) of deciduous forest on the Millar Western FMA area.



7.1.2 Ecological Natural Subregions

The Millar Western FMA area includes three NSRs, but only the Central Mixedwood and Lower Foothills have enough area to be relevant to NRV results at this coarse scale.

The Central Mixedwood NSR historically had a large amount of young forest, and relatively small levels of mature and old forest (Figure 15). This is a function of the lower LTFC (65 years) for this area (Figure 2). Currently, almost 65% of the forest in the Central Mixedwood is immature, which is beyond that observed in the model. Another 19% is mature forest, which is within, but on the high side of NRV. The current levels of both old and young forest are at or very close to the lower threshold of NRV (Figure 15).

Figure 15. Historical ranges (box plot) and current levels (red dot) for the Central Mixedwood NSR on the Millar Western

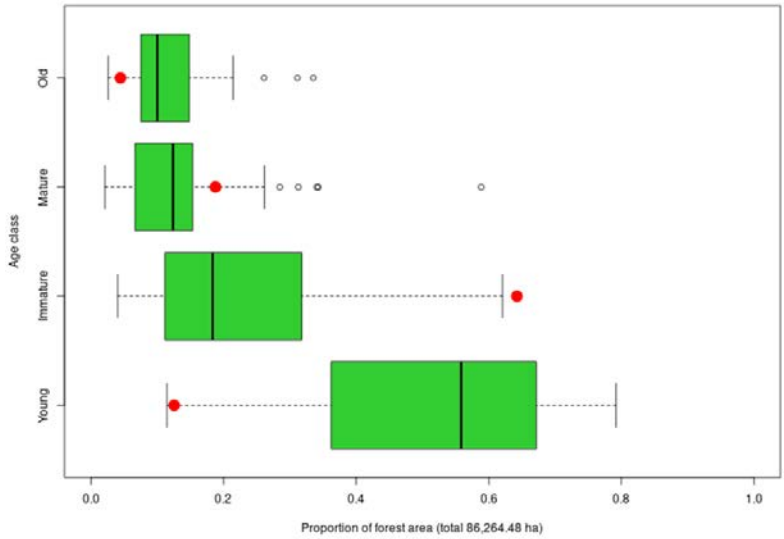
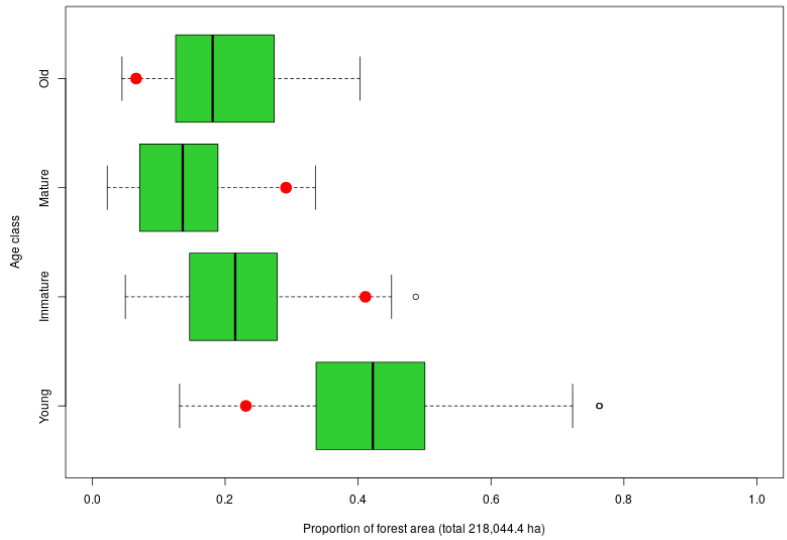


Figure 16. Historical ranges (box plot) and current levels (red dot) for the Lower Foothills NSR on the Millar Western FMA



As with the Central Mixedwood area, the Lower Foothills part of the study area, most of the forest is either immature or mature, and old and young forest levels are on the lower end of NRV (Figure 16). However, in this case all of the current conditions are within NRV. Note also the lower levels of young forest in the Lower Foothills historically relative to the Central Mixedwood (medians of 42% and 56% respectively).

7.1.3 Woodland Caribou Ranges

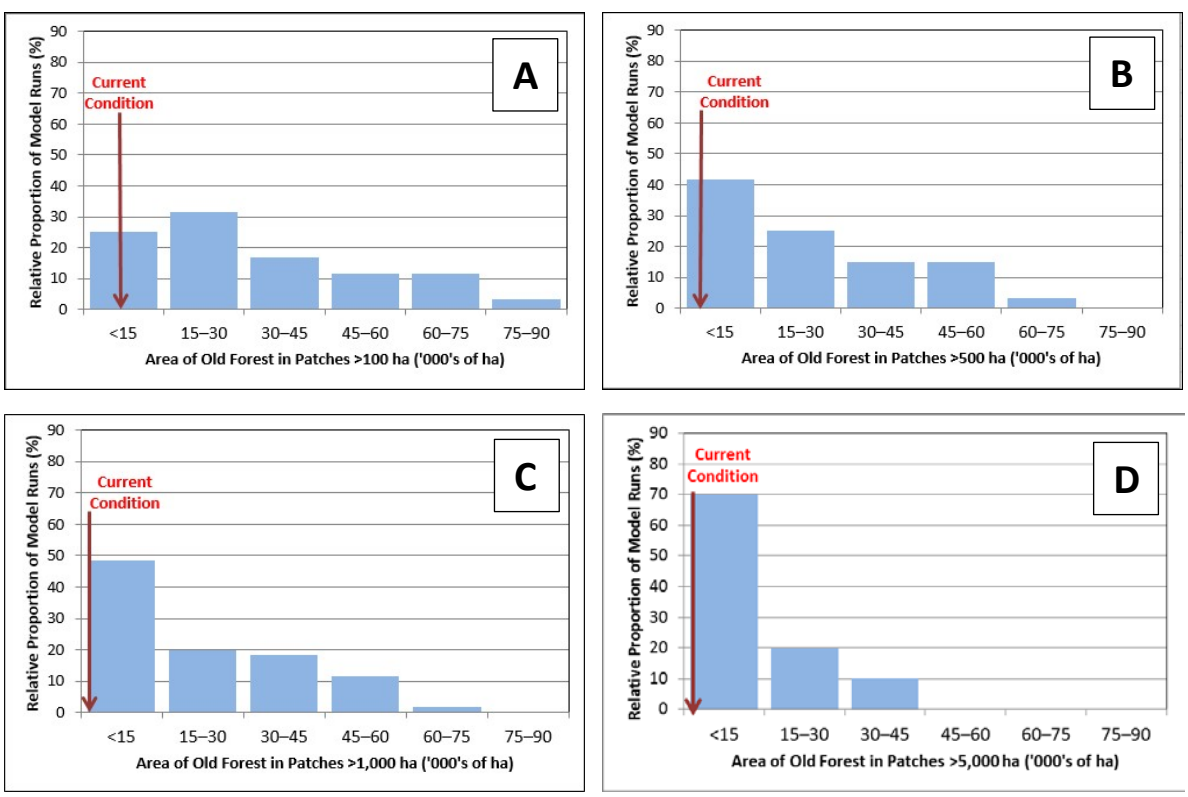
The Millar Western FMA overlaps with a small part of the Slave Lake caribou range. The area is not large enough to be relevant to NRV at this scale and is not shown here (but see Appendix A for the data).

7.2 Spatial Results

The results for four patch sizes of old forest are presented here as the number of patches >100 ha, >500 ha, >1000 ha, and >5000 ha. A "patch" is in this case defined by that portion of NRV and current condition that lies within the boundaries of the Millar Western FMA area. Large forest patches that extend beyond the boundaries of any part of the FMA area were captured by the model, but not reported here.

The area of old forest patches on the study area >100 ha in size ranged between about 2000 and 86,000 ha historically compared to the 7500 ha observed today, representing the 5th percentile or NRV (Figure 17A). The area in old forest patches >500 ha historically ranged between zero and 69,000, compared to almost 2600 ha today, which is the 3rd percentile of NRV (Figure 17B). The pre-industrial area of old forest patches >1000 ha ranged from 0–63,000 ha, compared to almost zero ha today (which was observed once by the model) (Figure 17C). Lastly, there were historically between zero and 39,000 ha in large old forest patches >5000 ha on the Millar Western FMA, compared to zero today (Figure 17D). Note that zero ha of forest in patches larger than 5000 ha occurred 48% of the time historically.

Figure 17. NRV (blue bars) and current condition (red arrow) of the area in old forest patch sizes on the Millar Western FMA area. Top left (A) is all old forest patches >100 ha. Top right (B) is old forest patches >500 ha. Bottom left (C) is all old forest patches >1000 ha and lower right all old forest patches >5000 ha.



8.0 Discussion

D.W. Andison

8.1 Overall Patterns

There are several patterns of note. First, the amount of forest in the 40–80 year range (immature) is very high (representing about 47% of the study area), suggesting high levels of disturbance activity during that period. Provincial fire records suggest that a net area (i.e., including overburns) of 120,000 ha, or about 27% of the study area burned between 1940 and 1980. Most of this is from the 1960 Vega fire, and a large fire complex from 1951. However, keep in mind that reliable fire records in Alberta did not occur until around 1950, which means the actual amount of fire activity 40–80 years ago is likely higher than 120,000 ha. However, even using 27%, and assuming the proportion of burned areas reflect proportions of forest areas, that means about 20% of the disturbance in this 40 year period was due to anthropogenic activities — or about 0.5% / year.

The low level of old forest relative to NRV is also notable. As above, this is due to some combination of natural and anthropogenic disturbance activities that focused on old forest. The most significant natural event over the last 40 years is the 1998 Virginia Hills fire, which burned about 40,000 ha. However, it is unknown what the pre-fire seral-stages were. The other possibility is that anthropogenic disturbance activities such as harvesting occurred largely in older forest.

The last notable pattern is the relatively low level of young forest. The level of disturbance over the last 40 years is on the low side of NRV. The 1998 Virginia Hills fire accounts about 40,000 ha, or about 9% of the FMA area. Again, very roughly assuming that fire area equates to forest proportional area, that means about 12% of the young forest is due to anthropogenic activities.

The spatial results suggest that the FMA area lacks larger old forest patches (of any size) relative to NRV. However, recall that the total amount of old forest is on the low end of NRV. This is relevant because the amount of any given forest type (e.g., seral-stage, vegetation type) decreases, the chances of that forest type clustering deceases. In other words, large areas of old forest are more likely to create more and larger clusters of old forest. In this case, even if the entire 6% area in old forest were in a single large patch, it would only be about 25,000 ha. Thus, the issue is not how to create more area in large old forest patches, but rather the spatial arrangement of future old forest areas.

It should also important to know that the spatial analyses did not consider specific causes. Pickell et al. (2013, 2015) found that despite the fact that the disturbance footprint of the energy sector was quite low, the impact on the resulting landscape patterns was far beyond that of forest management because it was so spatially ubiquitous. There is also considerable public infrastructure in the study area in the form of development, but also many types of linear features (e.g., roads, trails, rights of way). The only way of understanding the impact of each of these factors on old forest patch size calculations is to conduct a more comprehensive and specific spatial analysis than this study was intended to provide.

Based on the observed and current patterns, what might this landscape might look like in another 20 years? First, some of the burned areas from the 1950's and 60's will shift from immature to mature and a portion of the mature forest will shift to being old. Depending on the forest types being disturbed, these changes may help create a more "natural" landscape ecosystem overall. However, young forest levels will be an important exception to this. Under a business-as-usual policy and harvesting scenario of about 0.5% harvested / year, in another 20 years, there will still be very low levels of young forest relative to NRV. In fact young forest levels will drop below the lower end of the NRV threshold without significant natural disturbance activity (e.g., wildfires, disease, insect outbreaks, etc.).

8.2 Species Types and the Active Land Base

The foundation of forest management in Canada has for many decades been built on the basis of *sustainable yield* (Monserud 2003). In practice, the sustainable yield means the harvest levels should never exceed the expected growth in a given time period, much like the concept of withdrawing only the interest from a bank account. The issue as it relates to sustained yield from an NRV perspective is that the calculation of the principal is based only on that part of the forest that is capable of being harvested at some point in the future; the so-called contributing or *active* land base. On the Millar Western FMA area, the "active" forest area accounts for only 59% of the land base.

In the absence of being able to differentiate the active from the passive landbase, the black spruce results will be used as a surrogate for passive forest areas as this forest type is not, and has never been targeted for forest management.

The current condition of the black spruce type is in fact the furthest from NRV. It is the only forest type that is (quite a bit) below the lower threshold of NRV for young forest. Assuming black spruce forest types roughly represent the passive forest, this means passive forest areas are further beyond NRV than other (active) forest types. As above, when the passive land base is extrapolated into the future another 20 years, the seral-stage imbalance becomes much more significant, and much more difficult to manage. An overly simplistic version is that disturbance drops to close to zero, and the current seral-stage levels progress over time, ultimately creating large amounts of mature and old forest.

In contrast, the current level of young pine is very close to the NRV median of 38%, which suggests pine has been a target for disturbance over the last 40 years. It is not known whether this is due to fire, mountain pine beetle mortality, or harvesting.

8.3 Possible Sources of Error in the Model

One of the most widely known quotes about modelling is from 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 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?

Keeping in mind both Box's advice and the concept of parsimony, recall that the purpose of this modelling exercise was to define some broad and simple landscape-scale, pre-industrial pattern metrics. Thus, the question is not so much whether the model simulated fire patterns, the probability of vegetative sprouting, or the distance of seed dispersal flawlessly, but rather which factors, parameters, or assumptions are mostly likely to *significantly* influence the desired output. Thanks to the simplicity of the model — and its purpose — the range of possibilities is limited. The issue of the model poorly representing forest types has already been discussed in detail in Section 6.6 along with possible sources of error, as well as possible solutions.

The next most significant factor driving the area of different seral-stages is the frequency of disturbance (i.e., the LTFC). To illustrate, using a simple negative exponential mathematical model that is broadly associated with representing age-class distributions in the boreal forest and no difference in relative flammability (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 of identifying pre-industrial LTFCs in the study area was thorough 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 2019). In the end, the LTFC map represents the best available science; although the confidence level of the final LTFCs varies by region. The confidence levels of LTFCs in this particular part of the LandWeb study area were a combination of very little local evidence, but much higher quality adjacent evidence. The experts agreed that the LTFC estimates for the study area are moderately reliable (Andison 2019). However, there is always room for improvement. 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 changing the LTFC numbers by plus or minus 5, 10, or 20 years on either side of those shown in Figure 2. This addresses the question; "*if we are wrong about LTFCs by X years, what would the impact be on our conclusions?"*

Another possible source of error could be the under-representation of low and moderate severity fires in the model. As with every other landscape-scale model today, the fire spread module in LandWeb captures and represents severity in a simplistic, binary fashion; either a pixel burns completely or not at all. However, evidence suggests that some percentage of historical fires left behind significant areas of partially burned forest (Andison 2004). This could influence succession dynamics in a number of ways. First, as residual forest levels increase, the "regeneration" components of the LANDIS succession model are less relevant, based on time-since-fire alone. For example, a 70 year old forest that experiences only 30% mortality from a fire will clearly be functioning as a sexually mature forest type, with a shade tolerant and re-sprouting understorey. Second, the introduction of low to moderate severity fires

challenges, and suggests expanding on, simple definitions of a seral-stage to capture more complex forest age structures such as definitions of "old growth". Partial mortality is also likely to complicate the definition of habitat types (Amoroso et al. 2011), perhaps most notably as it relates to woodland caribou (Environment Canada 2012).

Another possible source of error is with the current condition estimates. Current conditions for the non-spatial results (i.e., the red dots) were taken from the most recent forest inventory available to the research team at the time of modelling — which may not be the same as more recent estimates. This is easily addressed by upgrading the current condition "red dots".

There are two challenges inherent in the calculation of current condition for patch sizes. The first is tracking, classifying, and dating each disturbance feature. As with age data, AVI does not prioritize capturing details on all types of these data as part of its primary purpose. Fortunately, other agencies (e.g., the Alberta Biodiversity Monitoring Institute) 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 for the current condition estimate of patch sizes is more daunting: How to integrate and compare the impacts of forest edges of different sources and ages? For example, if/how do we differentiate edges along highways from a bush road, a large, new seismic line, or 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 several alternative "edge" scenarios, perhaps using the ABMI data.

8.4 Implications

The seral-stage condition of this landscape is not beyond NRV, but close to being so. In theory, a landscape that is close to, or has already shifted 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).

The issue in this case is an age-class imbalance; not enough young and old, and too much immature and mature. Diversity is generally 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 seral elements (i.e., richness) has not changed relative to NRV, but the current proportion of each (i.e., evenness) 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 proportions of habitat types over time and space. EBM theory suggests that pushing a landscape system (too far) beyond this natural range is likely to create some unexpected and likely negative outcomes for the resident species and services (Pickett et al. 1992).

In this case, there are both over and under-represented habitat types on the Millar Western FMA area today relative to NRV. The under-represented seral-stages include both old and young forest. The ecological value of old forest is well recognized and documented (e.g., Goulden et al. 2011). Less well recognized is the ecological value of young forest (Kuuluvainen and Gauthier 2018). Young forest

provides critical habitat and environmental conditions, and the soil nutrient profiles necessary for the existence of a large number of boreal species 1–5 years after wildfire (e.g., Coop et al. 2010, Yeager et al. 2005). Landscapes with proportions of young or old forest below those experienced historically are thus likely to be less healthy and resilient.

The implications of a potential shortage of large old forest patches identified in this study are relatively well understood. Similar to the logic (above) for ecotype distribution, there are a range of species that prefer forest edge and those that prefer forest interior (Magura 2002). We also know by association (i.e., the lack of large contiguous patches) that the amount of forest edge currently in the study area exceeds, or is on the high end of, anything ever experienced historically. Unless the interior forest dependent species are able to adapt, it is reasonable to presume that the population levels of such species will decline. The decline of contiguous old forest patches in the boreal is neither a new pattern, nor a surprising one (i.e., Pickell et al 2016). However, as noted above, larger old forest patches are only possible when the amount of old forest is high enough.

Equally concerning is the longer-term implications of the status quo management scenario with respect to natural disturbance risk. The historical base rate of harvesting in the 0.5% / year range is far below the natural, historical study area average of about 1.3% / year. In the absence of any change to the status quo, the inevitable outcome will be increasing areas of older forest that are more susceptible to natural disturbance. Some, but not all, of this is due to a lack of disturbance in the passive forest areas (as per provincial fire control objectives).

9.0 Recommendations

D.W. Andison

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

1) **Use the results from this study as an early warning system for ecosystem health concerns.** If nothing else, this project reveals if and how patterns at landscape patterns have momentum that may seem benign, or even entirely missed in the absence of an NRV analyses. The impacts of those pattern changes (negative or otherwise) on fine filter values such as species and wildfire risk are often only obvious many years or decades later, at which point management become reactionary. Our current, “value-based” management systems force us to continually be responding to known, existing threats. Shifting to a more proactive NRV-based management based on NRV is the ultimate manifestation of a *precautionary principle*.

2) **Change the channel on the role / importance of disturbance**. This landscape needs more disturbance activity relative to NRV. For too long, disturbance has been largely associated with 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 in the form of simplistic thresholds (for example).

3) **Consider a sensitively analyses with different LTFCs.** Although the LTFCs used for the modelling had a moderate level of agreement among fire regime experts, it can always be improved upon with related historical fire regime research. Adjacent tenure holders may be willing and able to support such research as part of the HLP.

4) **Finalize model testing and validation.** The stand-type succession problems encountered with the model do not significantly affect the overall pattern of results for this study. However, reconciling the original succession module formulation should be a priority. Although the answer(s) may not impact the findings from this study, this will help make the LandWeb model more valuable and defendable as a tool going forward.

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APPENDIX A: TABULAR QUARTILE RESULTS

Table A1. Historical quartile and current range of major vegetation types on the Millar Western FMA area.

Vegetation Type	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (Percentile)						
			MIN	12.5%	25%	50%	75%	87.5%	MAX
All species	Young	21	18	30	35	46	53	61	73
	Immature	47	8	13	16	21	28	36	40
	Mature	26	3	6	8	14	17	21	28
	Old	6	5	10	13	17	24	29	38
Black Spruce	Young	12	20	31	38	46	55	62	73
	Immature	49	8	13	16	22	27	34	40
	Mature	31	3	6	8	13	17	20	27
	Old	7	5	10	13	16	24	28	39
Deciduous	Young	20	16	28	32	41	53	58	70
	Immature	49	11	15	19	28	34	41	58
	Mature	25	2	6	8	13	17	23	31
	Old	5	4	8	10	14	21	23	34
Mixedwood	Young	21	22	34	41	51	61	68	79
	Immature	42	6	12	15	21	27	34	39
	Mature	28	2	5	7	12	16	20	26
	Old	8	3	8	10	14	21	24	33
Pine	Young	35	14	23	30	38	47	50	65
	Immature	51	9	14	17	23	28	39	42
	Mature	12	4	8	11	16	21	25	33
	Old	2	7	13	16	20	27	31	41
White Spruce	Young	19	17	27	34	43	53	58	72
	Immature	43	8	15	17	24	30	38	44
	Mature	32	3	7	9	14	19	23	33
	Old	7	4	10	12	16	23	26	32

Table A2. Historical quartile and current range by ecological natural subregion types on the Millar Western FMA area.

NSR	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (Percentile)						
			MIN	12.5%	25%	50%	75%	87.5%	MAX
Central Mixedwood	Young	13	11	30	36	56	67	73	79
	Immature	64	4	9	11	18	32	41	62
	Mature	19	2	4	7	12	15	25	26
	Old	4	3	6	8	10	15	19	21
Lower Foothills	Young	23	13	27	34	42	50	61	72
	Immature	41	5	11	15	22	28	37	45
	Mature	29	2	5	7	14	19	21	34
	Old	7	4	11	13	18	27	33	40
Upper Foothills	Young	44	4	11	17	35	53	66	89
	Immature	41	1	5	11	19	30	40	54
	Mature	10	1	3	4	8	16	25	33
	Old	5	3	7	11	21	42	54	76

Table A3. Historical quartile and current range by woodland caribou ranges on the Millar Western FMA area.

Caribou Range	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (Percentile)						
			MIN	12.5%	25%	50%	75%	87.5%	MAX
Slave Lake	Young	11	4	19	37	60	75	81	94
	Immature	77	1	4	7	15	28	50	58
	Mature	10	1	2	3	8	20	30	42
	Old	2	0	2	4	8	16	21	33