FINAL REPORT

Understanding Historical Landscape Patterns on the Alberta Newsprint Company 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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EXECUTIVE SUMMARY

This project was a spatial modelling exercise that created coarse-scale pre-industrial landscape metrics for the Alberta Newsprint Company (ANC) 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 much of the landscape is now beyond its historical range. More specifically, the amount of mature (80–120 years) and old (>120 years) was in many cases currently beyond the upper natural range of variation (NRV) threshold, and the overall amount of young (<40 years) forest was close to or beyond the lower NRV threshold. More detailed analyses revealed that the deviation from NRV was more pronounced in those parts of the landscape that were not actively managed for timber. This suggests that wildfire control efforts have been effective for several decades. However, even those parts of the landscape that were managed for timber show the same deviation pattern from NRV, suggesting that historical harvesting levels + natural disturbance levels on the ANC FMA area have been lower than historical disturbance rates for several decades.

While a large amount of older forest can provide positive benefits to a landscape in the form of a buffer against natural disturbance and critical habitat (e.g., for woodland caribou), it also increases the risk of natural disturbances such as wildfires or insect and disease outbreaks, which ironically translates into a greater risk of loss of caribou habitat. A less obvious, but equally important implication of this study is the lack of young forest habitat. While we tend to focus on old forest as the ultimate measure of biodiversity, 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. 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. The impact of the loss of this habitat, and the associated species, has not been widely represented in past research efforts — but probably should be.

Of even 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 of the difference between NRV and current condition 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, c) the risk of natural disturbance agents, and by association, d) the ecological, economic and social health of forested ecosystems. And, if anything, we should be even more concerned about the future. Species responses to significant habitat deviations can take much longer to occur and to observe, revealing one of the key weaknesses of a value-based management approach; it often becomes largely about triage. In contrast, one of the benefits of NRV comparisons is that it functions as an early-warning system for threats to sustainability.

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 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 (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 multiple 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 one to explore how known (observed) 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 describes a modelling process by which we generated multiple possible historic landscape scenes, summarized their patterns, and compared those to the current landscape condition for the ANC FMA area. The larger modelling project is LandWeb; *Landscape dynamics of Western Boreal Canada*. ***Note that each subsequent section of this report has been written by different authors.***

2.0 GOAL

By: D.W. Andison

The goal of the LandWeb project is: ***to understand some simple pre-industrial landscape-scale patterns on 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 ANC FMA area.

3.0 DESIRED CONDITIONS AND OUTCOMES

By: D.W. Andison

3.1 INDICATORS

The 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 on 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 GoA provincial standard, and agreed to by everyone, which were 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, >1000 ha, and >5000 ha. Patches should be reported by all forest types combined.

The LandWeb partners also asked to have NRV results summarized via several different geographic boundaries including a) jurisdiction (which includes the ANC 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 compared to the current condition since it 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 then 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 the inventory data from multiple jurisdictions across Canada (Cosco 2011). Although this database was not 100% complete, and some of the data outdated, it still saved us considerable time and costs. We acquired any outstanding data directly from partners as necessary.

3.3 CREATING A PRE-INDUSTRIAL CONDITION BASELINE

Given that the goal of the modelling is to create 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 rules in a hierarchical manner: 1) historical (pre-disturbance) vegetation information on digital data, 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 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, cut blocks, mines, and other human developments were replaced by attributes of the last known, or the most likely, polygon. The "natural" pre-industrial snapshot created by this process still likely 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 several centuries. To eliminate this risk, the model was run forward in time several thousands of years before landscape snapshots were collected and measured for NRV.

4.0 ANC STUDY AREA

By: D.W. Andison

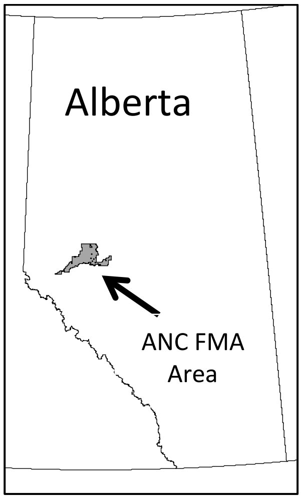
The area of concern for this report was the ANC FMA area, covering a total of almost 359,000 ha (Figure 1). Of the total area in the FMA area, almost 30,000 ha or about 8%, was non-forested.

Ecologically, the ANC area is dominated by almost equal parts of the Upper Foothills and Lower Foothills natural subregions (48% and 47% respectively), and 4% each of the Central Mixedwood and Subalpine NSRs (Table 1).

Table 1. Summary of ANC FMA area by Natural Subregions (NSR)

NSR Name	ANC FMA Area	
	Hectares	%
Subalpine	15,253	4
Central Mixedwood	16,123	4
Lower Foothills	170,284	47
Upper Foothills	172,116	48
TOTAL	**358,523**	**100**

Figure 1. Study area map showing the ANC FMA area.



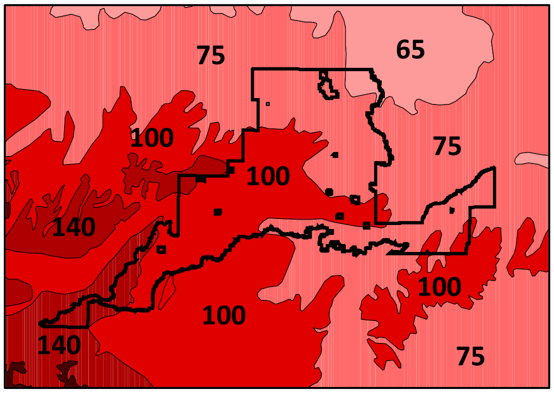
The range of ecological conditions across the ANC FMA area is relevant to fire history and thus also to NRV estimates. It spans an elevation from 200 m to over 1300 m, growing degree days from 800–1250, 500–760 mm of annual precipitation, and level to steep topography (Table 2).

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

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
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
	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
	Upper Boreal highlands	650-1150m	Upper slopes and plateaus	Short, cool, wet summers with cold, snowy winters	Coniferous forests (Pl-Pj, Sw, Sb) with extensive wetlands	Luvisols with organics and gleysols	950	560	2.8

Nor is the ANC study area homogeneous in terms of historic (or future) fire behaviour or risk. For example, estimates of the average pre-historic long-term fire cycle ranges from 65–140 years across the study area (Figure 2). Furthermore, there is a strong alignment between the long-term fire frequency estimates and many critical wildfire elements. For example, shorter fire cycles are associated with low elevation (i.e., higher lighting ignition probability), and longer growing (and fire) seasons.

Figure 2. Long-term-fire-cycles for the ANC FMA area.



5.0 METHODS: CHOOSING A SPATIAL MODEL

By: 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 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 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 by 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 capture /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 hectares).

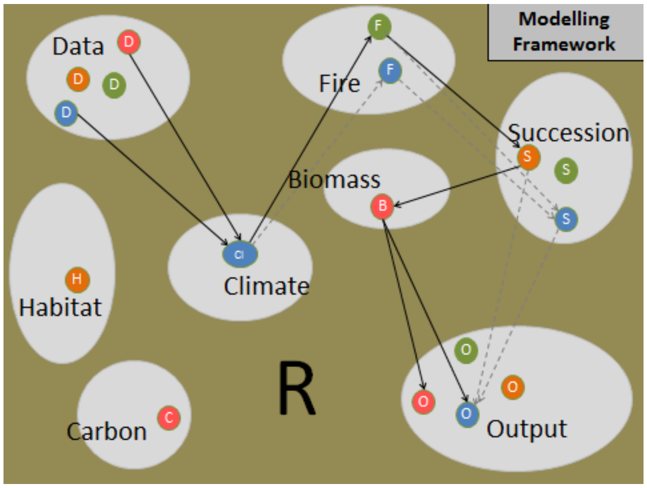
These requirements were quite restrictive, and narrowed the field considerably since it meant the model must be a) raster-based at a scale of no larger than 10 ha, b) able to function across multiple fire regimes, c) able to handle and integrate multiple spatial data sources, and d) highly efficient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

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 talk to each other (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 in 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 talk to each other, and even 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 and use of a universal spatial model for other purposes. Third, the plan for LandWeb in SpaDES was to create a stand-alone app available (free of charge) online to anyone. Lastly, 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 adopting 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 and validating and error-checking code is notoriously challenging and time-consuming, and in this case there was no shortage of new territory and technical challenges to be 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 present 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

By: A.M. Chubaty and E.J.B. McIntire

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 in the east, and from the southern boundary of the forest-grassland interface roughly to the 62nd parallel into the Northwest Territory. 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) (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 by ecozone.

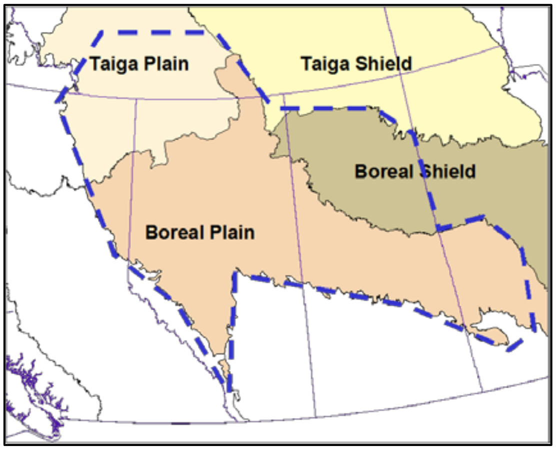
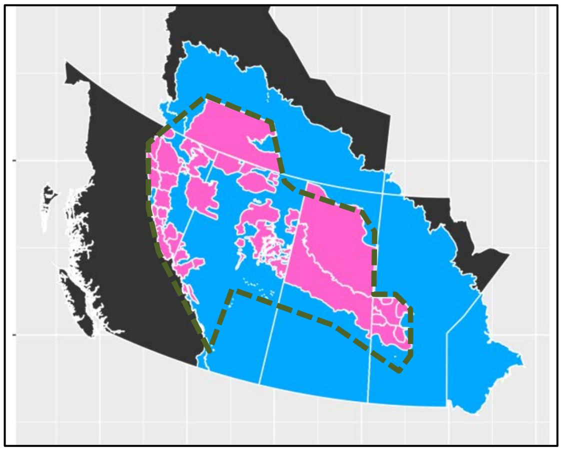


Figure 5. Map of the LandWeb Study Area showing the modelling area (blue) and current caribou range (pink).



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 is simply acting as an orchestrator to schedule and run various modules.

Although individual modules are designed to be standalone units, their design includes several features that integrates their use with other modules. 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 (the configuration of parameters and data dependencies) used by LandWeb 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 (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 historic NRV. In developing the model, analyses, as well as the infrastructure to host data, we attempted to implement a single, reproducible workflow to facilitate running simulations, analyses, and 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.

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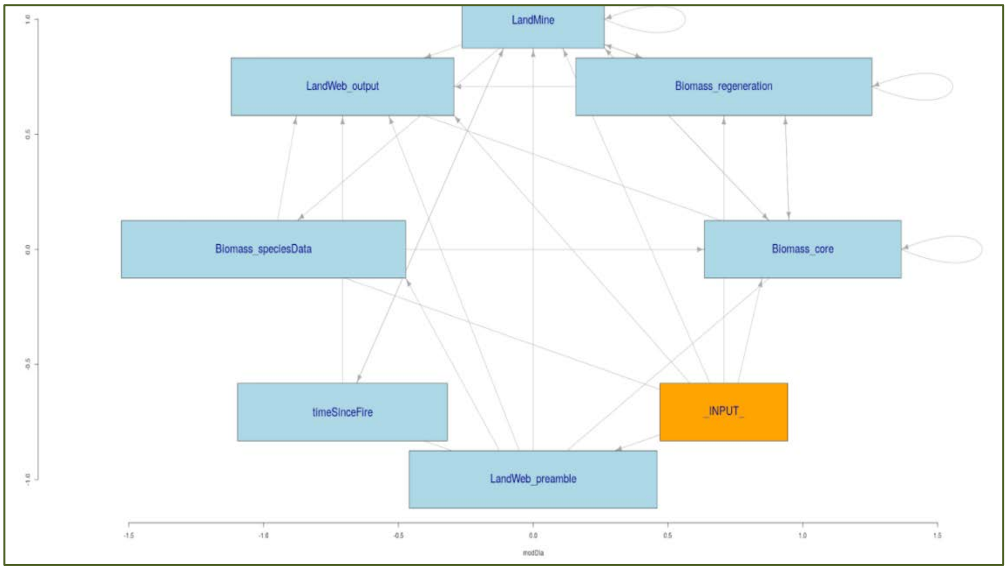
[1] Packages used includes, SpaDES, SpaDES.core, SpaDES.tools, reproducible, quickPlot, LandR, LandWebUtils, amc, pemisc, map, raster, sp, sf, and data.table

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 (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 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) 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 to ensure 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 spp*), 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 (see table) and overlays them to produce single cover layers by species. It also performs several data pre-processing steps to ensure 1) all data use the same geospatial geometries, 2) all data are cropped to the study area, and 3) any inconsistent or missing data are corrected or fill-in based on the data from the 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 in Table 6.

As above, this module defaults to processing cover data for five species/genera: fir, white spruce, black spruce, pine, and trembling aspen.

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) 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 imputed 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 units of biomass (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., last year's disturbances) 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 regeneration, in this case after fire events, assuming stand-replacing fires. 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 shade given all biomass was totally removed after fire) (see Table 8 for species trait values). The module algorithm first assessed 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 for which species that rely on re-sprouting will do so depending on whether they are within 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)

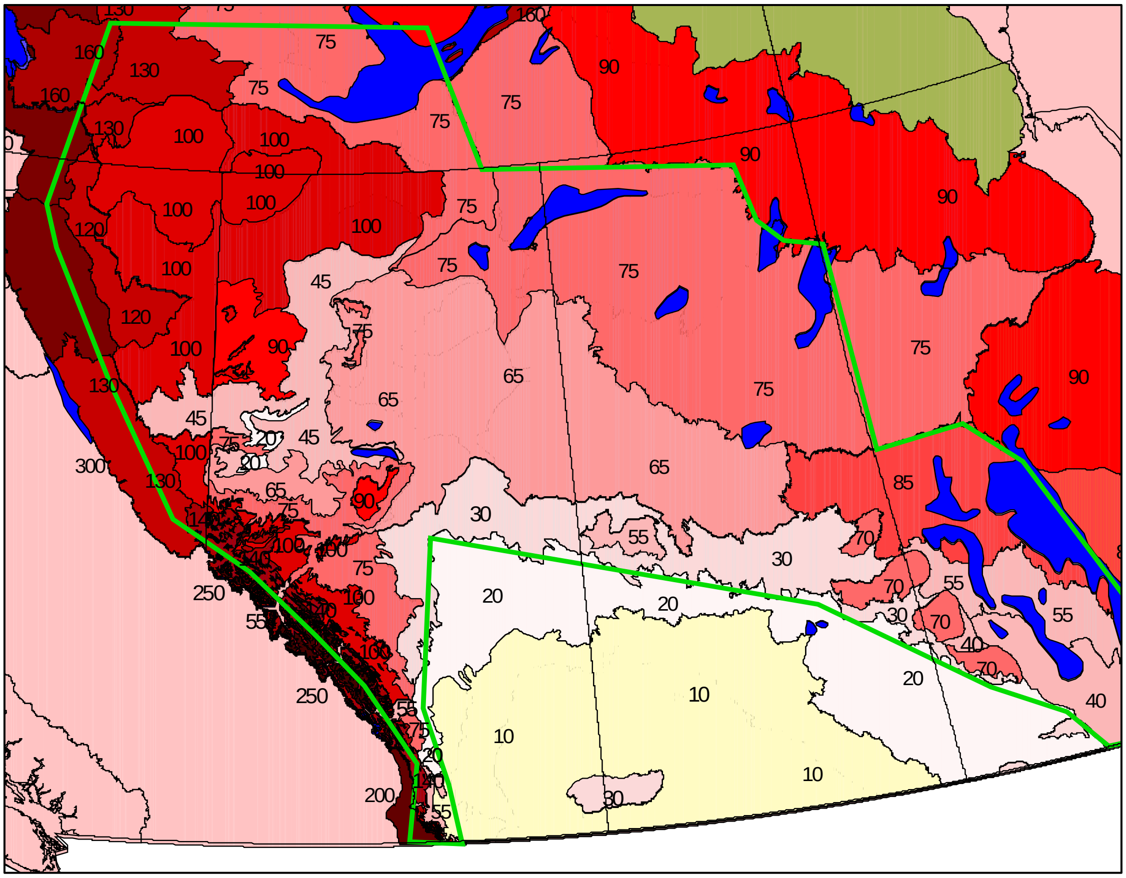
Having insufficient data to draw from, we assumed that the overall proportion of each species in the landscape doesn't change much over the course of the simulation. Our previous simulation runs showed that stand regeneration — using the LANDIS-II defaults, when coupled with the fire dynamics (described below) — was inadequate to ensure that the proportion of each species across the entire landscape remained consistent with current conditions data. Rather than re-engineer the underlying LANDIS-II approach to simulating these dynamics, we instead focussed on re-parameterization of 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 what resembles state-transition model formulation, used successfully in ecology for years.

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 simulating the natural range of variation for landscapes in the boreal forest (Andison 1996; 1998; Clarke, Brass, and Riggan 1994), and has been widely used by the public and private sectors in various contexts; in particular for NRV models. It takes as an input a map of the Long-Term Historic 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., to remove vegetation it burns). The LTFCs are used as fire return intervals in the simulations (Table 9).

Figure 7. Map of long-term historic fire cycles (years) for the LandWeb study area.



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 the neighbourhood for burnable pixels until it reaches its assigned fire size. If it gets stuck, it "jumps" to nearby pixels for 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 compare 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 are unburnable, have a non-flammable cover class 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 reached. 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 calculates 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 runs 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, parks, and FMA boundaries. Second 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 simulated several thousand years, taking and measuring snapshots at 700, 800, 900, and 1000 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. In this case, this first version of LandWeb created landscapes that shifted some vegetation types beyond that which was expected. In this case, it mostly reduced the area of pine and increased the amount of fir (*Abies spp.*).

This was unexpected, and suggested one or more model parameters, assumptions, or data inputs were not being accurately represented. This prompted a thorough and lengthy review of 1) code and algorithms, 2) data, 3) parameters, and 4) 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 force the succession module to maintain (on average) the proportion of vegetation types observed on the landscape today. In doing so, this affected not only the results, but the function of the model itself.

The LANDIS succession module that we used for LandWeb is a type of “vital attributes” model (sensu Noble and Slatyer 1980), in which changes in vegetation are a result of life history attributes of species such as seed dispersal timing and distance, re-sprouting, sexual maturity, and shade tolerance. In this study, the parameterization of these species attributes was simplified to the point where the succession module functioned more as a state transition model (STM). Changes in vegetation in STMs are a result of a series of probabilities of broad vegetation types transitioning from one state to another (i.e., hardwood to mixedwood) (Stringham et al. 2003).

The likely implications of, and recommendations related to, this challenge are discussed further in Section 8.1.

7.0 RESULTS

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7.1 NON-SPATIAL RESULTS

The non-spatial results from the NRV modelling results are presented as *box and whisker plots*. 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. 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. The 50th percentile is called the median. In Figure 8 below, the first quartile is the 'whisker' dotted line on the left, the second quartile the green box left of the black vertical line (the median), the third quartile the green box on the right, and the fourth quartile the (dotted line) whisker on the right. Note also in Figure 8 there are also small open circles. These are known as *outliers* because they are significantly higher or lower than the rest of the data.

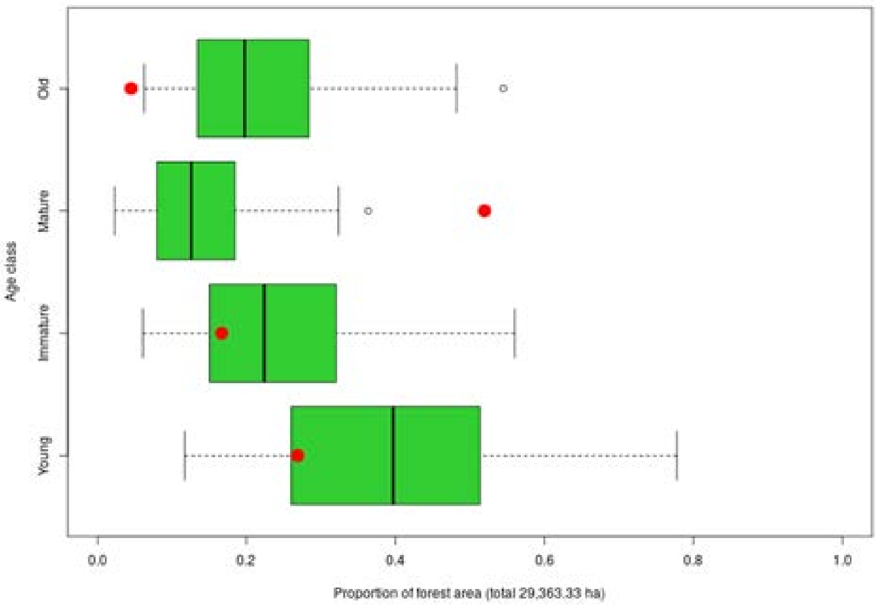


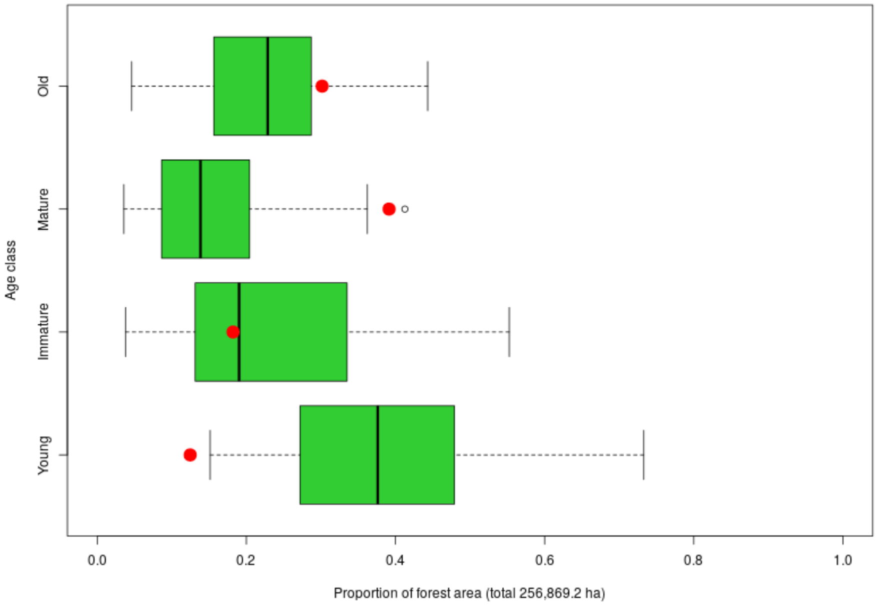
Figure 8. Historical (box plot) and current range (red dot) of pine forest on a sample study area — just for demonstration.

Box and whisker plots not only simplify output into a more visually intuitive form, but also allow viewing all seral stages at the same time. For example, each set of four quartiles represent all four seral-stages of a specific vegetation type. The associated area (in hectares) of the vegetation type is shown in brackets in the x-axis title. In this case, there was 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.

Figure 9. Historical (box plot) and current range (red dot) of all forest on the ANC FMA area.

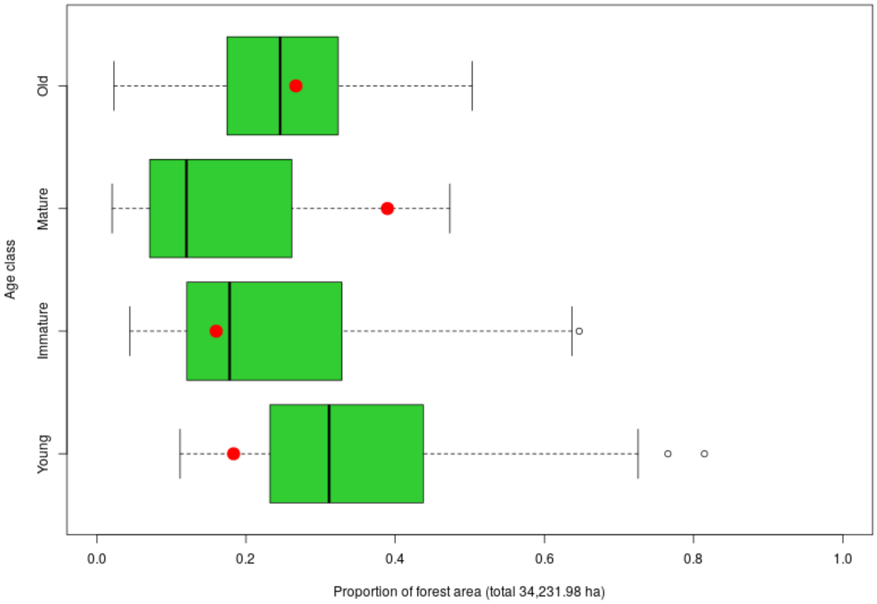


Overall, only two of the four forest seral-stages on the ANC FMA area are currently within NRV. The current level of old forest at 30% lay just beyond the third quartile of NRV, and the 18% immature forest is almost exactly the NRV median (Figure 9). In contrast, the current 12% of young forest was below the minimum observed in the NRV data, and the 39% of mature forest was only exceeded once during the simulation exercise.

7.1.1 MAJOR VEGETATION TYPES

The following results break down the ANC FMA area by four of the six forest types as per Section 4.0.

Figure 10. Historical (box plot) and current range (red dot) of pine forest on the ANC FMA area.



Current pine-dominated forest levels were within NRV for all seral stages, although the mature forest levels were over the 90th percentile of NRV, and old pine was close to the 10th percentile (Figure 10). Both old and immature forest levels were currently close to the NRV medians.

Historical levels of young black spruce forest were significantly higher than that currently observed. Currently, 5% of black spruce forest was <40 years old, compared to a median of 34% historically (Figure 11). On the other hand, both old and mature areas of black spruce were beyond the 90th percentile of NRV. When old and immature black spruce forest levels were combined, their current level is well within NRV (Figure 11).

Figure 11. Historical (box plot) and current range (red dot) of black spruce forest on the ANC FMA area.

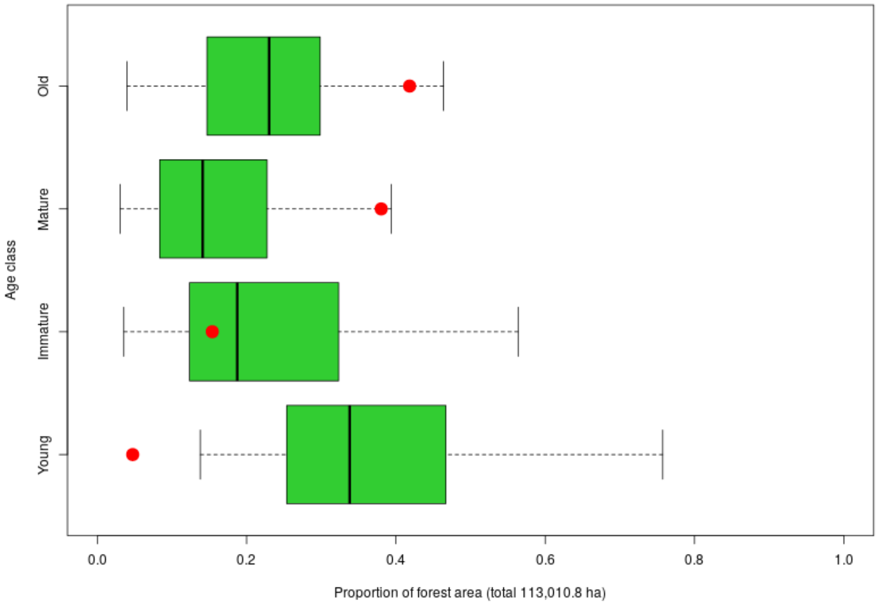
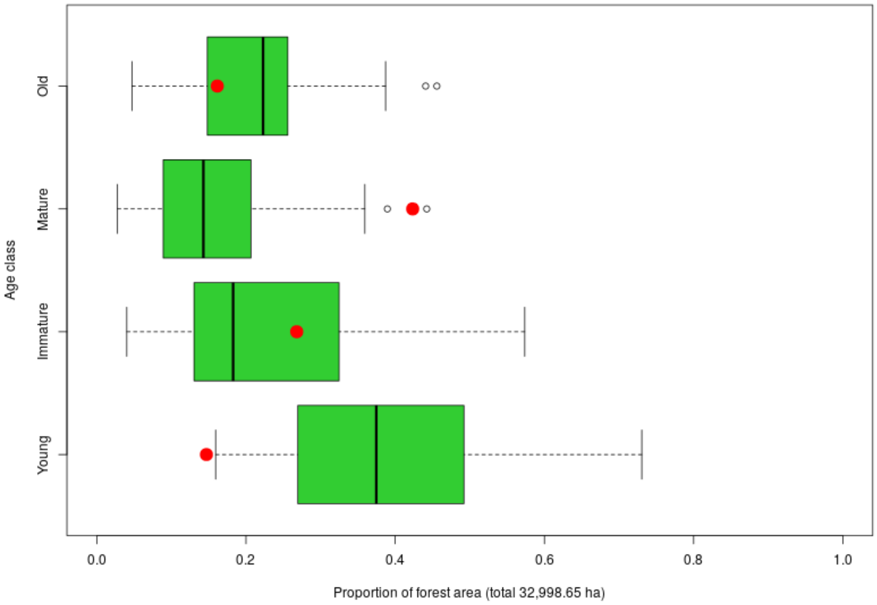


Figure 12. Historical (box plot) and current range (red dot) of mixedwood forest on the ANC FMA area.



Mixedwood forest levels were well currently within NRV for old and immature forest (Figure 12). However, the current level of 42% of mature forest was only exceeded once by the modelling. The current 15% young forest is lower than the lower threshold of NRV and well below the NRV median (Figure 12).

The pattern of insufficient young forest and large amounts of older forest continues. The current level of young white spruce forest (5%) was well below the lower threshold of NRV. The amount of old (45%) matched the maximum observed from the NRV modelling, and mature white spruce was above the 95th percentile of NRV (Figure 13).

Figure 13. Historical (box plot) and current range (red dot) of white spruce forest on the ANC FMA area.

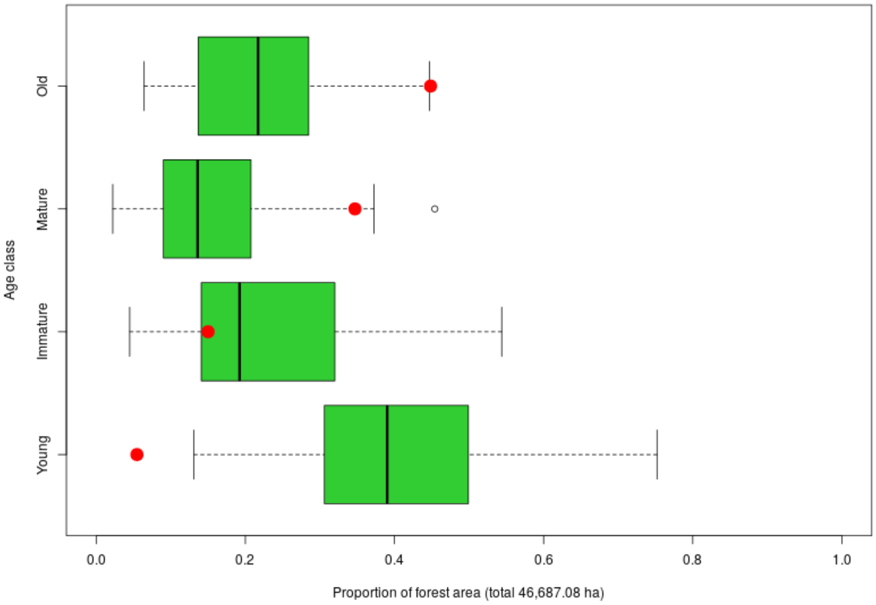
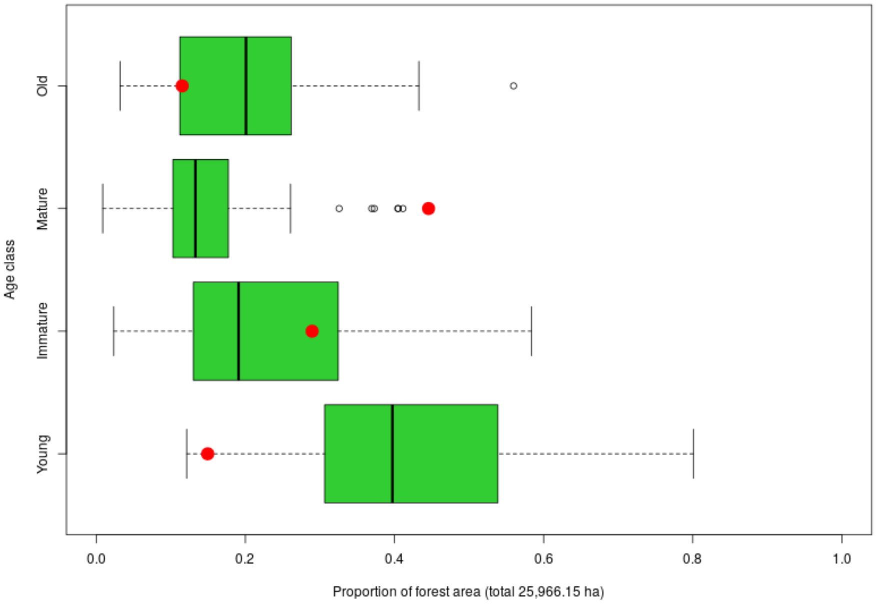


Figure 14. Historical (box plot) and current range (red dot) of deciduous forest on the ANC FMA area.



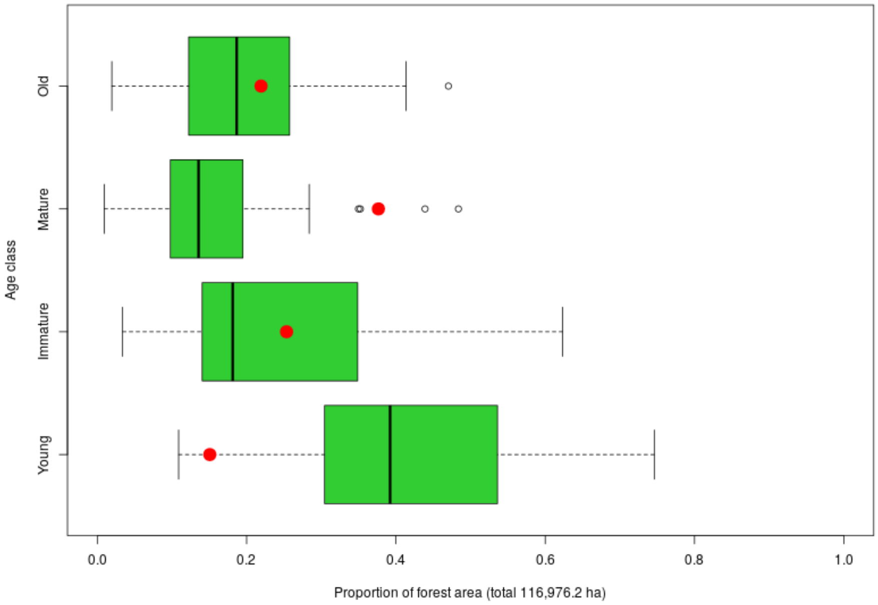
Current levels of young deciduous forest on the ANC FMA area (15%) were below the 5th percentile of NRV from the modelling exercise. The amount of mature forest currently observed was well beyond the upper threshold of NRV (Figure 14). The amount of both old and immature deciduous forest on the ANC FMA were well within NRV.

7.1.2 ECOLOGICAL NATURAL SUBREGIONS

The ANC FMA area includes four NSRs, but neither the subalpine nor the central mixedwood include enough area to generate useful NRV estimates (see Appendix A for these data).

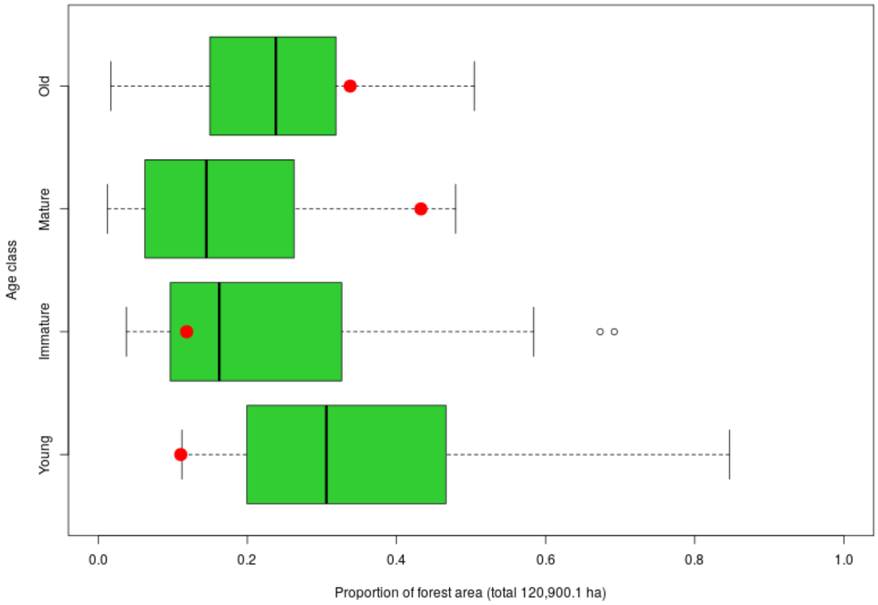
The current amount of young forest in the Lower Foothills NSR modelling (15%) is close to the lower NRV threshold, and the 38% mature forest beyond the upper end of NRV (Figure 15). Both old and immature forest levels were currently well within NRV according to the simulation output.

Figure 15. Historical (box plot) and current range (red dot) for the Lower Foothills NSR on the ANC FMA area.



The Upper Foothills NSR followed a similar pattern as the Lower Foothills, with very high levels of mature forest, and very low levels of young forest relative to NRV (Figure 16).

Figure 16. Historical (box plot) and current range (red dot) for the Upper Foothills NSR on the ANC FMA area.

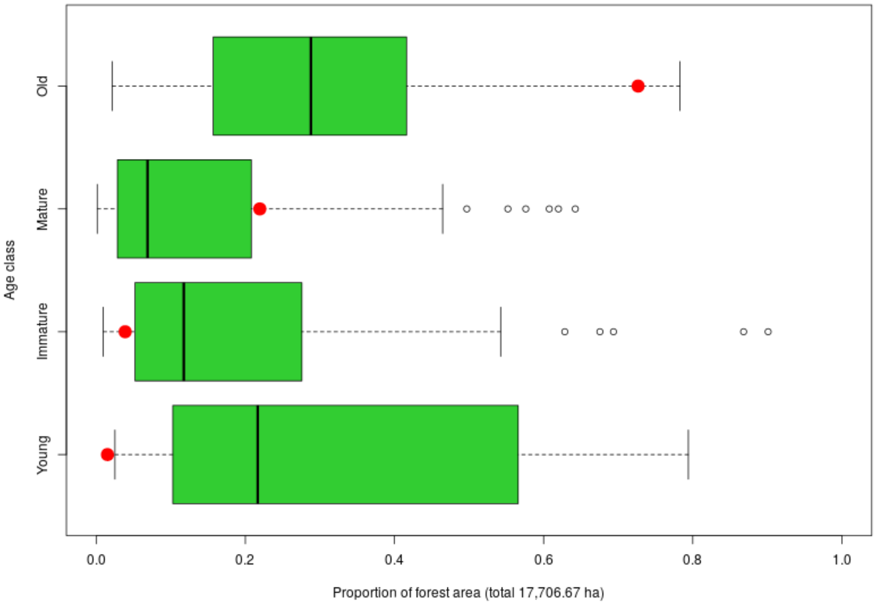


Also note the differences in NRV between the two NSRs. Median NRV of young forest was 31% for the Upper Foothills, compared to 39% for the Lower Foothills. The difference is due entirely to the difference in LTRC (100 vs 75 years respectively). The longer Long Term Fire Cycle (LTFC) in the Upper Foothills was also reflected in the lower old forest median in the Lower Foothills (19%) relative to the Upper Foothills (24%).

7.1.3 WOODLAND CARIBOU RANGES

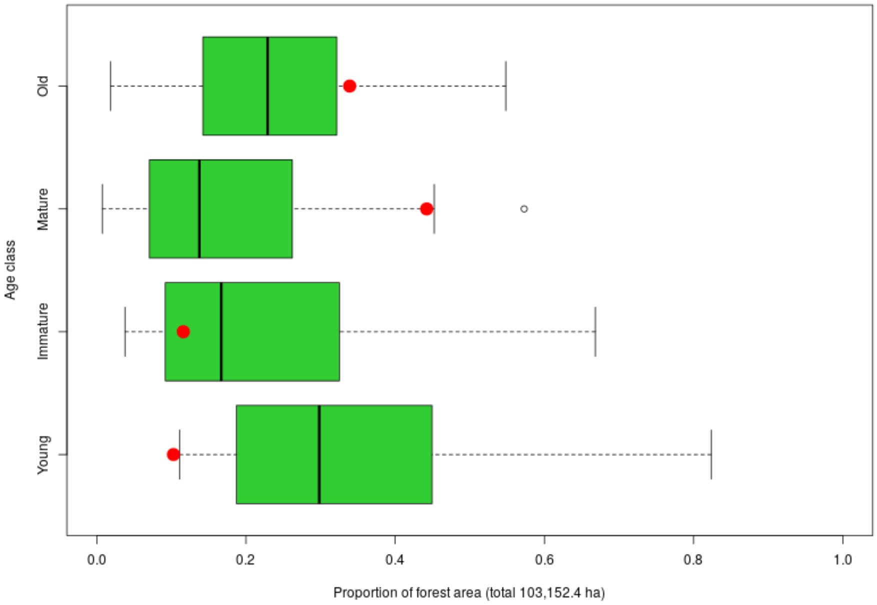
The ANC FMA overlaps with two caribou ranges, the A La Peche and the Little Smoky.

Figure 17. Historical (box plot) and current range (red dot) for the A La Peche caribou range on the ANC FMA area.



The current level of young forest (i.e., <40 years old) within the ANC FMA portion of the A La Peche range was 2%, which is not only below NRV, but well below the 35% maximum suggested by federal guidelines for defining suitable caribou habitat (Environment Canada 2012). It is also interesting to note that the modelling results only produced landscape scenes with more than the 35% maximum threshold of young forest about 40% of the time (Figure 17). In other words, the (ANC portion of the) A La Peche range was historically unlikely to support a viable woodland caribou population about 40% of the time according to federal guidelines. The massive amount of older forest in this area is also notable. The current levels of forest in the ANC portion of the A La Peche range older than 80 years is 95% — which is well beyond anything observed historically.

Figure 18. Historical (box plot) and current range (red dot) for the Little Smoky caribou range on the ANC FMA area.



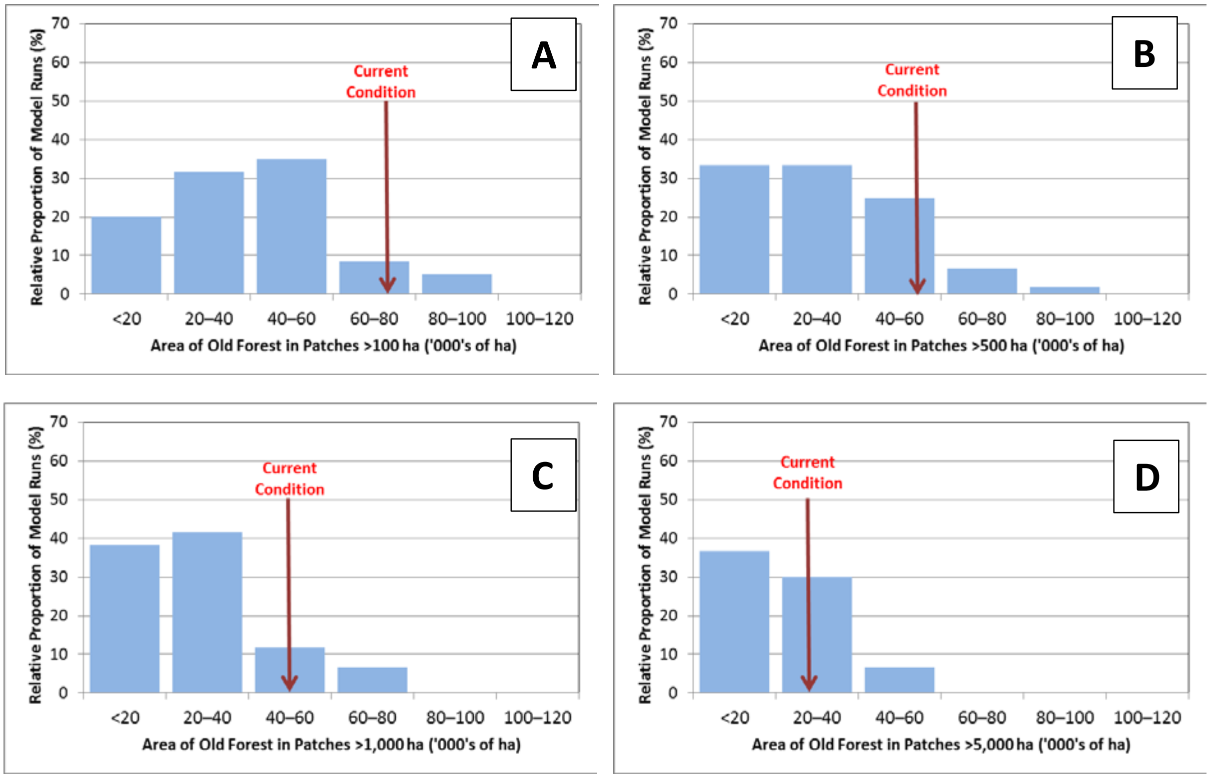
The current amount of forest <40 years of age in the Little Smoky range is 10%, which is also below the lower boundary of NRV, and well below federal maximum of 35%. In contrast, forest older than 80 years of age currently accounts for 78% of the Little Smoky area of the ANC FMA area, which is far beyond anything experienced historically (Figure 18).

7.2 SPATIAL RESULTS

As a reminder, 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. Moreover, a "patch" in this case captured only that portion of NRV or current condition that lies only within the boundaries of the ANC FMA area. Large forest patches that extend beyond the boundaries of the FMA area were captured by the model, but not reported.

Current levels of old forest area in larger patches are all within NRV. The area of old forest patches on the study area >100 ha in size ranged between 4,500 and 92,000 ha historically compared to just over 73,000 ha observed today (Figure 19A). The area in old forest patches >500 ha historically ranged between 1,000 and 82,000 ha compared to 55,000 ha today (Figure 19B). The pre-industrial area of old forest patches >1,000 ha ranged from 0 to 75,000 ha, compared to 12,000 ha today (Figure 19C). Lastly, there were historically between zero and 59,000 ha in large old forest patches >5,000 ha on the ANC FMA, compared to almost 10,000 ha today (Figure 19D).

Figure 19. NRV (blue bars) and current condition (red arrow) of the area in old forest patch sizes on the ANC 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

By: D.W. Andison

8.1 MODEL VALIDATION

As described in Section 6.5, the succession module of LandWeb was creating unexpected species profiles. In this case, the model ended up with much higher levels of fir, and much lower levels of pine than there exist today, or anytime in the last several decades.

One of the model assumptions made at the start of the project was that the current proportions of vegetation types reflect the average of pre-industrial vegetation patterns. After several months of attempting to reconcile this through error checking and manipulating parameters, the solution was to simplify the succession module to emulate a state transition model. However, as the ANC output reveals, this still created some significant vegetation type shifts that suggests this solution was imperfect.

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

1) The assumption that the average pre-industrial landscape conditions will reflect the current vegetation breakdown 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 (such as fire frequency).
2) The LTFC estimates (used as model inputs) were wrong. Since fir is well known to only be able to become a dominant species is under very long LTFCs, this suggests that the LTFCs used in the model were far too short.
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 and fir to invade.
4) There are still un-discovered errors in the model.
5) There are missing parameters in the model that may be relevant.
6) The resolution (i.e., pixel size) of the model was too large to capture the scale at which the relevant dynamics (of 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 (mirroring the same numbering reference as above):

1) There may be some 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 significant — in

particular to decline of pine. Still, testing this hypothesis is important, and would benefit from the inclusion of a (validated) climate module.

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 incomplete. In an effort to address these gaps, a related but independent research project developed the LTFC map used as input for the model using a combination of the available empirical evidence, and the opinion of a large number of fire regime experts over four years of input (Andison 2019). And, although the quality of the evidence varies across the study area, for the ANC area, it is at least of moderate quality (i.e., at least moderate confidence in the LTFCs used). So it is possible that some of the LTFC numbers used for model calibration may not be accurate. Having said that: a) there are several parts of the study area with high quality and broad historical fire cycle data, and b) the final numbers used to calibrate LandWeb captured the mid-point of any relevant disagreements among the experts if and when empirical data was scarce (i.e., it is just as likely that actual LTFCs are lower than those in Figure 7 than higher). Testing this hypothesis is a simple matter of replacing the existing LTFC map with one or more alternatives until the output reveals a relatively consistent proportion of forest types. The challenge in this case is that such an analysis may find LTFCs that make the succession module "work", but would contradict the evidence from a wide range of published papers, unpublished reports, available data, and the opinion of many experts.
3) The boreal has long been 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 regeneration and growth attributes. The fire spread module used in LandWeb was based on the one from Landmine, but it was not calibrated to survival levels. This is another model parameter well worth testing through a sensitivity analysis.
4) One can never be 100% sure that there are not errors. 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. Similarly, the Landis model was created and tested largely in the eastern boreal, which have far longer LTFCs than in the LandWeb study area. 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 model parameters is difficult to evaluate, which makes it a constant source of potential error. Just because a module is mechanistic (i.e., captures 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 far 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 "properly" than it is to be confident that the various parameters are pieced together in a robust manner.
6) One of the ways in which LandWeb is unique is that it attempted to blend fine-scale with coarse-scale dynamics. This inconsistency may be the price we are paying for attempting to do so. 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 is not likely to be accurately represented at a scale of 6.25 ha without significant testing — which was not done. Thus, cell or pixel size is another obvious candidate for a sensitivity analyses.
7) The succession module was calibrated to represent the entire LandWeb study area. In fact, the climatic, ecological, and wildfire dynamics conditions vary widely. Whereas in the past a single calibration exercise was feasible for smaller study areas, the LandWeb study area may require multiple, unique calibrations.

In the end, all possibilities described above are legitimate candidates to explain the model output discrepancies.

As important as it is to find the source(s) of the inconsistency described here, it is important to understand that this particular modelling issue was very unlikely to significantly impact the results. Recall that the output metrics were both simple and broad. For example, note that 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, going forward, this issue will have a much greater impact on more detailed landscape metrics or future studies using this model that include more specific habitat types, climate, or carbon modelling.

8.2 Interpreting the 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 for the ANC FMA area 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 older forest today relative to historical conditions***.

In terms of the details, the overall current levels of old forest are mostly within NRV, and create 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 mostly within NRV. The concern is the fact that the current levels of mature forest are mostly well beyond the upper bounds of NRV. When old and mature are combined, they are almost universally beyond NRV, regardless of whether it is broken down by vegetation, NRV, or caribou range. In other words, this landscape is already unbalanced relative to historical conditions. And barring any significant increases in disturbance levels, inventory age data suggests that a large proportion of mature forest will shift to old forest in the next 10–20 years. 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, Weyerhaeuser, Alberta government, Mercer Peace River Pulp, and Mistik Management in Saskatchewan.

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 (BAU) scenario in which nothing changes as regards policies and practices and project forward another 20 years. Recall that the current level of 12% of young forest (<40 years of age) is well below the lower end of NRV. For context, the NRV median is more than three times higher. If we use the disturbance levels of the last 40 years as a benchmark for the future, we know that an average of (12%/40 years =) 0.3% 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 × 0.3 =) 6% 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, this simplistic scenario described 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 the FMA area were quadrupled, the amount of old + mature forest combined would still be beyond NRV in 20 years. However, under this scenario one must account for the potential catastrophic social and economic costs 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 spatial results suggest that the numbers of large old forest patches are within NRV, although on the lower side for the largest patches. However, there are three challenges associated with the interpretation of the spatial results. First, recall that the amount of old forest is on the high side of NRV for the study area. As the amount of old forest area increases, the likelihood of higher proportional area in larger patches increases. The patch size distributions shown in this report only reflect the full range of old forest levels.

Second, the rules governing the boundaries of a “patch” were very simplistic. For example, linear features were not classified by type, width, or age. Thus, a 20-year old 3m seismic line represented a “boundary” in the data in the same way that a 100m highway ROW did. Yet most species would respond to these linear features very differently. Lastly, the protocols for including linear features within inventory data are constantly evolving, which means the vintage of the data used to calculate the current condition is relevant. More recent and accurate data are likely to produce different current condition data.

The second challenge is that the spatial analyses consider specific causes. This is particularly relevant to the spatial results because of the activity in this part of Alberta by the energy sector. 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, etc.). The only way of divining the influence of each sector on old forest patch size is to re-do the calculation of current condition using a series of baseline assumptions based on classifying anthropogenic features.

In the end, while the analyses here offers a reasonable first glimpse at old forest patch sizes. the only way of understanding the impact of each of the three challenges above is to conduct a more comprehensive and specific spatial analysis than this study was intended to provide.

8.3 THE DETAILS

The specifics of how NRV compares to current conditions for the ANC landscape are highly informative. The foundation of forest management in Canada is built on the basis of sustainable yield (Monserud 2003). In practice, this 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, but not the principal. The issue in this case is that the calculation of the principal is based only on that part of the landscape that is capable of being harvested (at any given time). Alberta refers to these actively managed bits of the landscape as “contributing” forest. The remaining forest areas are referred to as “passive”, and will never be harvested. On the ANC FMA area, the contributing area accounts for about 65% of the forest area. So, for the sake of argument, about two-thirds the forested area for ANC is being managed for a sustainable flow of wood fibre based on the principle of sustainable yield. In an ideal world, this assumes that a) the maximum annual allowable cut is achieved (on the *contributing* land base), and b) natural vectors such as wildfire, insects, and disease will uniquely and appropriately disturb the remaining 1/3 of the FMA area. The results from this study suggest that neither assumption is true today.

In the absence of information on passive *vs* contributing for the ANC FMA area, the results from the black spruce cover type can be used as a surrogate for passive forest areas, since few if any of these areas have ever been actively harvested. Recall that current black spruce forest levels are well beyond the lower threshold of NRV for young forest. This is not entirely unexpected given not only the absence of harvesting, but decades of very high success rates of fire control. Since these areas are currently not economically viable for the forest industry, this means either allowing more fires to burn under controlled conditions, more prescribed fires, introducing alternative forest product streams that encourage disturbance in passive forest areas (e.g., for pellets), or non-commercial mechanical disturbance. Otherwise, the gap between current and historical conditions will only continue to widen on this part of the ANC landscape.

However, the same pattern is noted in the vegetation types that are typically targeted as *contributing* forest. Recall that three of the five vegetation types had young forest levels below the lower threshold of NRV, and the other two were no higher than the 5th percentile (Section 7.1.1). In other words, harvest + natural disturbance levels have for several decades been much lower than the average disturbance levels that occurred historically.

The details of NRV and current condition for the two caribou ranges in the study area were also highly informative. The current level of “recovered” forest (>40 years of age) was 98% for the A La Peche range, and 90% for the Little Smoky, both well above 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 do not include the impact of linear features and the associated buffering. Having said that, the NRV results were still very informative. 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 60% of the time for the A La Peche range and 64% for the Little Smoky. This suggests that neither range supported woodland caribou continually over the last several hundreds of years.

These results suggest one of three explanations;

a) One or more modelling assumptions or methods in this study were tragically in error,
b) Woodland caribou historically moved around to alternative suitable habitat in response to natural disturbances, or
c) The assumption that any forest area that has experienced a disturbance of any type less than 40 years ago is unsuitable habitat for caribou is in error.

Option (a) is explored in more detail below. Further exploration of options (b) and (c) are beyond the scope of this study. But as with all good research projects, the fact that this study raises these very specific questions can only help provide keys to future caribou survival efforts.

8.4 POSSIBLE SOURCES OF ERROR IN THE MODEL

Section 8.1 provided a detailed breakdown of the possible reasons for the discrepancy between the original output of vegetation types and the expectation from the current condition. This section discusses possible sources of modelling errors more broadly.

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 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 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 possibilities are limited. The 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 (Johnson 1992), the average amount of forest older than 120 years with a 65 year 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 2019). In the end, the LTFC map represents the best available science; although as Andison (2019) points out, the confidence level of the final LTFCs vary by region. Having said that, confidence in the LTFC numbers for the ANC area are actually higher than the average for the LandWeb study area. Still, it is a question worth investigating further.

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. 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 7. However, the danger of changing LTFC assumptions in the model is that it will contradict a considerable amount of other evidence.

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 or it does not. 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 mature forest type as regards sexual maturity, shade tolerance, and re-sprouting. 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.

The last potential sources of error in the results are the current condition estimates. With regards to current condition for the non-spatial results (i.e., the red dots), the ages were 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). Perhaps more importantly, the data provided by ANC at the time of this project may now be outdated (and should be updated).

There are two challenges to the calculation of current condition for patch sizes. 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 other 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 differentiate edges associated with highways to those 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.

8.5 ECOLOGICAL IMPLICATIONS

In theory, a landscape that has already moved 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 point, the current level of forest >80 years of age on the ANC study area was far greater 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 and unpredictable 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. It is also notable that that this increased risk to natural disturbance agents 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 habitat types. When the results are translated into hectares, almost half of the ANC FMA landscape is close to or beyond anything experienced historically. From an ecological perspective, this represents a fundamental imbalance of landscape scale diversity.

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 adapted 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). For example, as discussed above, a large amount of older forest will create a higher risk to wildfire, insects, and disease. A less obvious, but perhaps equally important risk is *under-represented* ecotypes. We tend to associate ecological risk with the loss of *old* forest habitat. However, in this case the greater risk is actually the loss of *young* forest habitat. Although not widely discussed, the critical habitat and environmental conditions, and the soil nutrient profiles necessary for the existence of a large number of boreal species creates 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.

Notwithstanding the many outstanding questions, this project does offer one of the first landscape pattern overviews from an NRV perspective for the ANC area. Thus, the results offer a starting point for not only compliance discussions with key coarse-filter indicators, but also a foundation for methodological and ecological discussions of relevance, including next steps.

8.6 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 landscapes compare to historical ones at one point in time and space, but also their direction of travel. Projecting the study area seral-stage patterns forward in time over several decades suggests that current policies and practices will only take the ANC FMA area only further beyond NRV in the future. Existing requirements that limit disturbance within caribou ranges will only magnify this trend. 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.

8.7 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?** An 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 generally acknowledged that wetlands provide significant ecological benefits in the boreal, there are many gaps in our understanding of the details of those dynamics over time and space, particularly as it relates to wildfire. This can be resolved by more, and more direct investment in research on this topic area to help reduce this knowledge gap.

2) **What are the potential challenges and opportunities of staying the course with respect to policies and practices?** It is not difficult to project what these landscapes will look like 20 years in the future under business as usual (BAU) policies and practices and 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 increase, and the chances of maintaining critical habitat for woodland caribou will decline. What we are less clear on is what future landscapes might look like under alternative policy/practice assumptions. Spatial modelling technology 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 collaboration between forest and fire management. In the short term, any steps towards collaboration between these two otherwise (until now) independent government agencies can only be a positive contribution to addressing many of the trends and 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.

8.8 THE SPADES EXPERIENCE

Supporting a new and unproven model to deliver on the desired outcomes for such an unprecedented study area represented a considerable risk for the Healthy Landscapes Program. In a perfect world, new model development and validation times are far longer than those estimated. In this case, the fact that the development of not only the underlying SpaDES environment, but also the LandWeb app was largely in the hands of academic collaborators was a significant leap of faith.

The HL Program learned several valuable lessons, both positive and negative.

- Data acquisition, summary, and integration for the LandWeb study area took far more time than anticipated. Some of this was due to technical challenges, some to unforeseen data complexities, and some due to delivery delays with respect to approvals of data sharing agreements with the many partners.
- There was not nearly enough time allowed for model validation. Regardless of the reason or source, errors of many and varied sources from any new model should have been fully anticipated and built into time and cost estimates. This factor alone cost was responsible for at least a full year of the delay.
- Progress updates to the modelling partners should have been more frequent. BI-annual meetings were in hindsight not frequent enough to explain how quickly things were changing.
- The project should have had a dedicated LandWeb project team, the members of which who were willing and able to engage on issues of progress, timelines, and delays on a more continual basis.
- Despite the many delays, we were very fortunate with the modelling team. The (largely in-kind) modelling team efforts were considerable, focused, and leading edge. The modelling team is also among the most qualified in the world for this task.
- In the end, and despite all of the challenges and delays, *once the forest dynamics issues have been addressed*, the HLP will have a new (decision-support, research, and communication) tool at their disposal.

9.0 RECOMMENDATIONS

By: 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.** Landscape patterns have momentum that can take several years or even decades to occur. The impacts (negative or otherwise) on fine filter values such as species are often only obvious many years or decades later. In other words, our current “value-based” management systems force us to continually be responding to known, existing threats. Shifting to a more pro-active NRV-based management paradigm that tracks early-warning metrics lies at the heart of an EBM approach, and may be far more efficient and effective. 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 responses. We could and should be using coarse-filter patterns and directions as an early warning system to avoid future fine-filter emergencies as the only way to save species.

2) **Change the channel on the role / importance of disturbance**. 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, as well as social and economic values) is the *quality* of disturbance activities, not the *existence* of them, or simplistic thresholds. Within and beyond Canada this message is becoming more accepted, but all forest land management agencies should be highlighting the necessary and positive roles 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 partner (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 inter-agency 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 questions posed in the previous Section 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) **Stop requesting or waiting for “more evidence”. The results in this report are the best available evidence today - and defensible.** 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, these results represent the best available science of the day. There will always be better evidence, and no doubt some parts of 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.

7) **Finalize testing and validating the model.** As previously stated, fortunately, 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 against empirical data should be a high priority. Although the answer(s) may not impact the findings from this study, this work will be necessary for future extensions of LandWeb.

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APPENDIX A: TABULAR QUARTILE RESULTS

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

Vegetation Type	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (%)				
			MIN	Q1	Q2 (median)	Q3	MAX
All species	Young	12	15	27	38	48	73
	Immature	18	4	13	19	34	55
	Mature	39	4	9	14	20	36
	Old	30	5	16	23	29	44
Black Spruce	Young	5	14	25	34	47	76
	Immature	15	4	12	19	32	56
	Mature	38	3	8	14	23	39
	Old	42	4	15	23	30	46
Deciduous	Young	15	12	31	40	54	80
	Immature	29	2	13	19	32	58
	Mature	45	1	10	13	18	26
	Old	12	3	11	20	26	43
Mixedwood	Young	15	16	27	37	49	73
	Immature	27	4	13	18	32	57
	Mature	42	3	9	14	21	36
	Old	16	5	15	22	26	39
Pine	Young	18	11	23	31	44	73
	Immature	16	4	12	18	33	64
	Mature	39	2	7	12	26	47
	Old	27	2	17	25	32	50
White Spruce	Young	5	13	31	39	50	75
	Immature	15	4	14	19	32	54
	Mature	35	2	9	14	21	37
	Old	45	6	14	22	28	45

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

NSR	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (%)				
			MIN	Q1	Q2 (median)	Q3	MAX
Central Mixedwood	Young	7	7	23	47	73	96
	Immature	28	0	5	12	25	54
	Mature	47	0	3	7	16	30
	Old	18	0	4	12	29	61
Lower Foothills	Young	15	11	30	39	54	75
	Immature	25	3	14	18	35	62
	Mature	38	1	10	14	20	28
	Old	22	2	12	19	26	41
Subalpine	Young	2	1	8	24	58	88
	Immature	2	0	3	12	25	58
	Mature	7	0	2	7	26	61
	Old	89	1	18	26	46	84
Upper Foothills	Young	11	11	20	31	47	85
	Immature	12	4	10	16	33	58
	Mature	43	1	6	15	26	48
	Old	34	2	15	24	32	50

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

Caribou Range	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (%)				
			MIN	Q1	Q2 (median)	Q3	MAX
A La Peche	Young	2	3	10	22	57	79
	Immature	4	1	5	12	28	54
	Mature	22	0	3	7	21	46
	Old	73	2	16	29	42	78
Little Smoky	Young	10	11	19	30	45	82
	Immature	12	4	9	17	33	67
	Mature	44	1	7	14	26	45
	Old	34	2	14	23	32	55