FINAL REPORT

Understanding Historical Landscape Patterns on the Mistik Management FMA Area in Saskatchewan

Final Report

fRI Research Healthy Landscapes Program

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David W. Andison, Bandaloop Landscape Ecosystem Services Ltd.
Alex M. Chubaty, FOR-CAST Research and Analytics
Eliot J.B. McIntire, Canadian Forestry Service

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EXECUTIVE SUMMARY

This project was a spatial modelling exercise that created coarse-scale, pre-industrial landscape metrics for the Mistik Management FMA area in Saskatchewan. 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 many parts of the landscape are now beyond its historical range. More specifically, the amount of both old and young forest are near or below the lower threshold of NRV, and the amount of immature and mature forest at or beyond the upper end of NRV.

Recent fire activity and forest harvesting likely contributed almost equally to the amount of young forest — although the total area disturbed from all sources in the last 40 years was still well below the pre-industrial median. The very high level of immature forest noted today is likely due to lack of timber management activities in these forests combined with some influence of fire control activities. The very low level of old forest observed today relative to that generated by the model is perhaps the greatest concern, but also raises the most questions. For example, the model did not account for the other insect, disease, and physical disturbance agents (many of which are age-dependent), or partial mortality from wildfire (which potentially complicates the definition of a seral-stage). Current condition estimates of age may have also been compromised by simplistic inventory sampling methods. There are enough unanswered questions as regards old forest levels to warrant further study before considering any significant altering of policies or practices.

In the end, there are multiple overlapping dynamics in play on this landscape that are relevant today. For example, the only reason the young seral stage is within NRV is a large area of unplanned and potentially costly wildfires. Going forward under a business as usual scenario, the amount of young forest will either drop well below the lower NRV threshold in the absence of fire, or stay within NRV, but only if a significant portion of the landscape (and its communities) experience costly wildfires. This suggests that fire and forest management activities should be better integrated towards a shared goal of ecosystem health.

1.0 INTRODUCTION

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

Under the auspices of this evolution, the concept of the using (pre-industrial) forest patterns created by natural processes as management guides is gaining favour in North America (Franklin 1993), and is one of the foundations of an ecosystem-based management (EBM) approach (Booth et al. 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 in time (Turner and Dale 1991, Payette 1993) and space (Andison and McCleary 2014). This means that historical levels of old forest are also likely to be both highly dynamic and spatially variable.

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

This report describes a modelling process by which we generated multiple possible historical landscape scenes, summarized their patterns, and compared those to the current landscape condition for the Mistik Management FMA area. The larger modelling project is LandWeb; *Landscape dynamics of Western Boreal Canada*.

2.0 GOAL

D.W. Andison

The goal of the LandWeb project is: ***to understand some simple pre-industrial landscape-scale patterns in the western boreal forest relative to the current condition***. Note that this goal is both narrow (it will capture only landscape scale patterns) and humble (it will capture only a small number of simple metrics). This report includes the results for the Mistik Management FMA area.

3.0 DESIRED CONDITIONS AND OUTCOMES

D.W. Andison

3.1 INDICATORS

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

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

In terms of old forest (i.e., >120 year old) patch sizes, the LandWeb partners also agreed that this project should report on the following patch sizes; >100 ha, >500 ha, >1000 ha, and >5000 ha. Patches should be reported by all forest types combined.

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

3.2 CURRENT CONDITIONS AS A REFERENCE POINT

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

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

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

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

3.3 CREATING A PRE-INDUSTRIAL CONDITION BASELINE

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

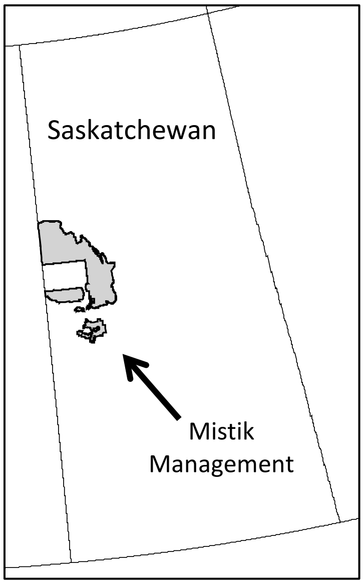
To create an initial pre-industrial landscape, we first obtained the oldest digital version of the forest inventory (with the least amount of cultural disturbance). Then we used digital data, records, and maps to replace cultural features with pre-disturbed vegetation types. Any remaining culturally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

4.0 STUDY AREA

D.W. Andison

The area of concern for this report was the Mistik Management FMA area, covering a total of just over 2,000,000 ha separated into four pieces (Figure 1). The larger northern piece is almost 1.6 million ha, or 79% of the total. Another 234,000 ha, or 9% of the FMA area lies just south of the Cold Lake Air Weapons Range, and 164,000 ha (12%) in the Bronson area to the south (Figure 1).

Figure 1. Study area map showing the Mistik Management FMA area.



Ecologically, most of the FMA area is in the Mid-Boreal Uplands ecoregion, with only 1% in the Boreal Transition (Table 1).

Table 1. Summary of Mistik Management FMA area by Ecoregion

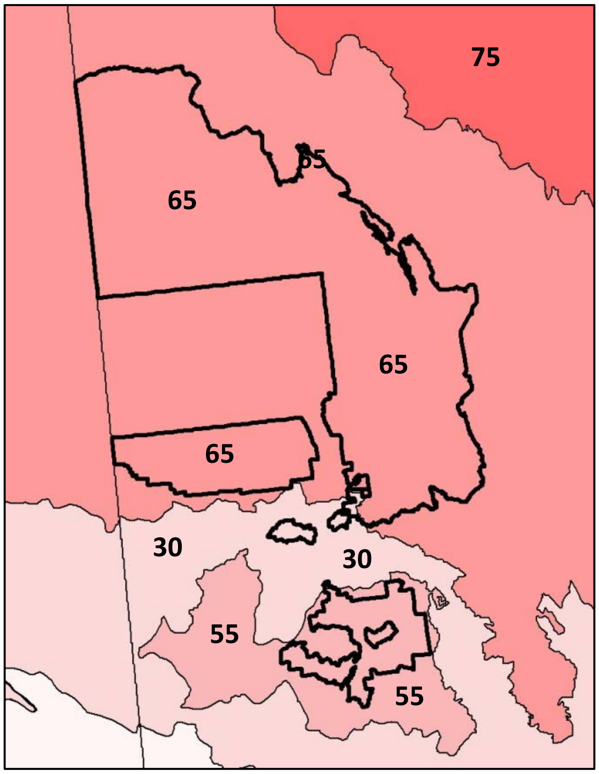
Ecoregion Name	FMA Area	
	Hectares	%
Boreal Transition	26,400	1
Mid-Boreal Uplands	1,984,995	99
TOTAL	**2,011,394**	**100**

Ecological conditions are relatively constant across the study area. Topography is relatively flat, with extensive wetlands, and the climate includes short warm summers and cold winters. The vegetation is classic boreal mixedwood forest with aspen, poplar, white spruce, black spruce, and A*bies* in areas undisturbed by fire for more than ~100 years (Table 2).

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

Ecozone	Ecoregion	Topography	Climate	Vegetation	Soils	Mean annual Precip (mm)
Boreal Plain	Boreal Transition	Hummocky to kettled plan	Warm summers and cold winters	Mostly aspen, poplar, and tall shrublands, with some white spruce and abies	Mostly Gray Luvisols and Dark Gray Chernozems	450-550
	Mid-Boreal Upland	Relatively flat with extensive wetlands	Short warm summers and cold winters	Mixed coniferous- deciduous forests of aspen, poplar, white spruce, black spruce, and some abies.	Mostly Eutric Brunisols and mesisols with gray luvisols	375-625

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



Estimates of the average pre-historical long-term fire cycle ranges from 55-65 years across the study area, although the majority is 65 years (Figure 2). However in contrast to the hard lines in Figure 2, it is more likely that actual fire activity becomes gradually more common as one moves from north to south.

5.0 METHODS: CHOOSING A SPATIAL MODEL

D.W. Andison

By definition, models are simple, incomplete representations of reality (Hammah and Curran 2009). There is also a key trade-off between complex models and simple ones. The "best" model is not necessarily the most complex or realistic one, but rather the model that best suits the purpose. The rule of parsimony for any modelling exercise ***is as complex as necessary, but no more***. In other words, each modelling exercise should focus on achieving the desired objectives with the least possible number of explanations, equations, and assumptions (Hammah and Curran 2009). In this case, modelling objectives were very simple and general in nature; to define the natural, pre-industrial range of a) seral-stage levels and b) patch sizes by broad vegetation types, and broad geographic zones. This requires a model with the following attributes:

1. Fully spatial,
2. Fully stochastic,
3. Able to function at multiple scales,
4. Very good at capturing known fire patterns,
5. Able to accurately 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 ha).

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

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

Another option presented itself at the same time. A CFS-Laval academic partnership (Drs. McIntire and Cumming respectively) were fleshing out the architecture of, and starting to write code for, an ensemble modelling framework called SpaDES (Spatially Discreet Event Simulator). Ensemble models are not models *per se*, but rather frameworks within which multiple models, and/or model components (i.e., modules) can interact (Krueger et al. 2012). In this case, the idea was to create a universal scheduling environment in R that would allow model modules (even ones from existing models) to communicate and be interchangeable. For example, in Figure 3, there are four different spatial data modules, two fire spread modules, and three forest succession modules to choose from (see below).

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

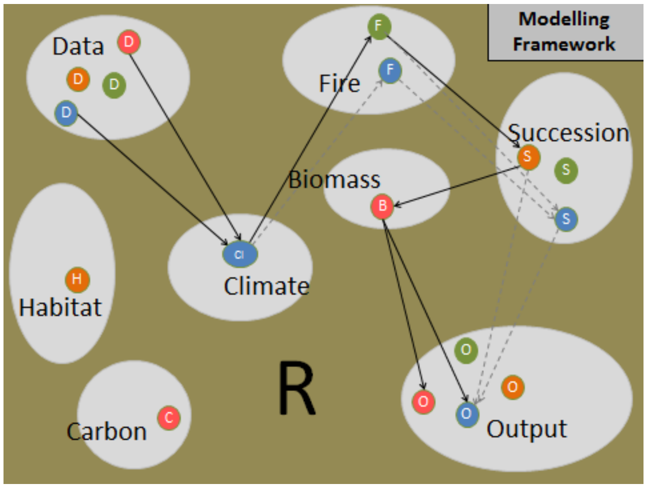


Figure 3. The SpaDES environment (brown shaded area) allows various modules to communicate and even be exchanged for other, parallel modules. The black lines represent one possible configuration of modules — out of dozens.

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

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

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

6.0 METHODS: LANDWEB AND SPADES

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 to the east, and from the southern boundary of the forest-grassland interface approximately to the 62nd parallel into the Northwest Territory. The area includes 73 million ha of Boreal Plain, 25 million ha of Taiga Plain, 20 million ha of Boreal Shield, and 7 million ha of transitional areas of Prairie, Montane Cordillera, Taiga Shield and Boreal Cordillera (Wilken 1986) (Figure 4).

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

Figure 4. Map of the LandWeb study area ecozones.

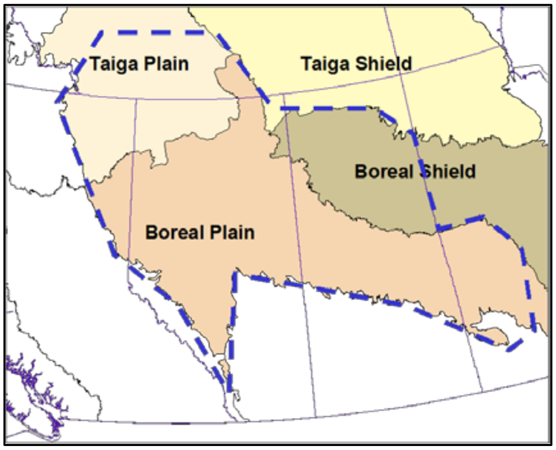
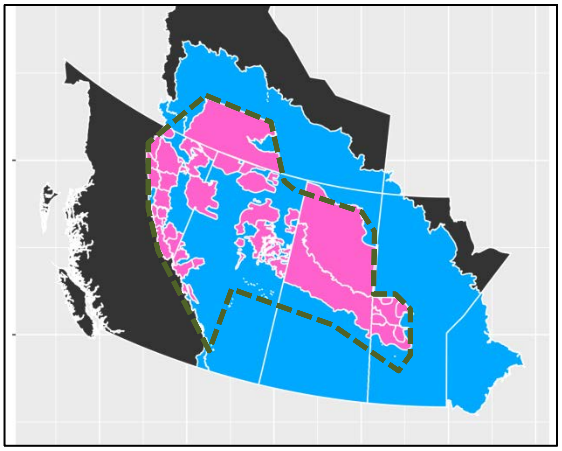


Figure 5. Map of the LandWeb Study Area showing the modelling area (blue) and current caribou range (pink).



6.2 SPADES

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

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

6.3 DATA SOURCES

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

Table 3. Summary of spatial data sources used

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

6.4 MODEL CODE

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

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

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

6.5 LANDWEB SIMULATION MODEL

6.5.1 OVERVIEW

To our knowledge, LandWeb is the first large scale, data-driven approach to simulating historical NRV. In developing the model, analyses, as well as the infrastructure to host data, we strived to implement a single, reproducible workflow to facilitate running simulations, analyses, model reuse and future expansion. This tight linkage between data and simulation model was made possible *via* its implementation using the SpaDES[1] family of packages (Chubaty and McIntire 2018; Chubaty 2019a; 2019b) 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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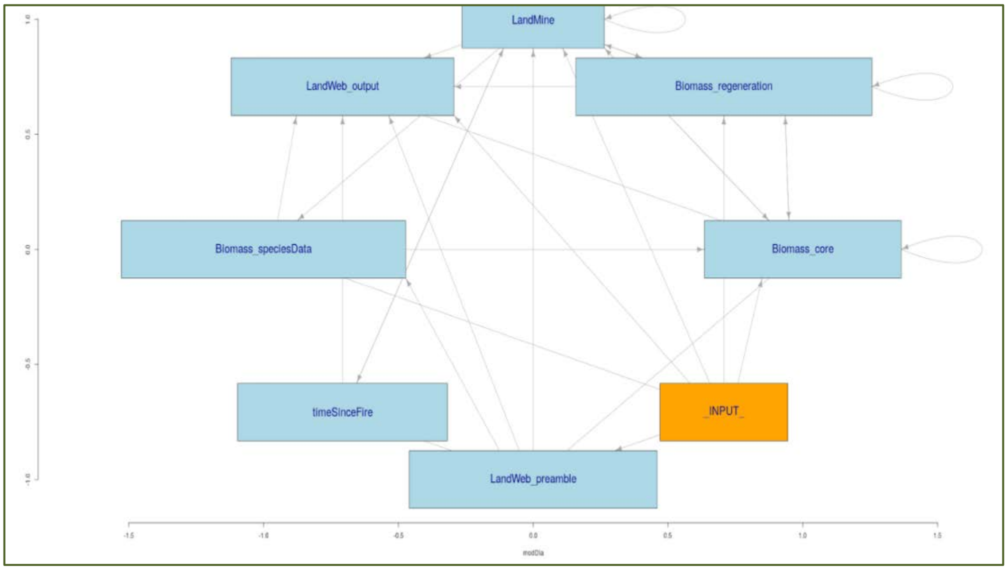
[1] Packages used includes, SpaDES, SpaDES.core, SpaDES.tools, reproducible, quickPlot, LandR, LandWebUtils, amc, pemisc, map, raster, sp, sf, and data.table

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, summarized in Figure 6 and are further described below.

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



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

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

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

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

6.5.2 Data preparation

The following describe the modules used for LandWeb.

6.5.2.1 LandWeb_preamble Module

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

The module defaults to processing cover data for five species/genera: fir (*Abies spp.*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), pine (*Pinus 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 (Table 5) 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) are cropped to the study area, and 3) attempts to correct or fill-in any inconsistent or missing data 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 (Table 5).

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

6.5.2.3 Biomass_borealDataPrep Module

This module converted open datasets that were available for all of Canada's forests into the input requirements for Biomass_core, a forest landscape succession model derived from the Landis-II Biomass

Succession Model (Scheller et al. 2007; Scheller and Mladenoff 2004). It was primarily used to estimate vegetation growth parameters including maximum biomass, maximum aboveground net primary productivity (aNPP), and seedling establishment probability, and to simulate the tree cohorts necessary for Biomass core. This module also provided other parameters, such as species tolerances to shade, and other plant traits (e.g., longevity, ability to re-sprout, etc.). These traits are the same as those derived from LANDIS-II, though the specific values used in the LandWeb simulations were 1) selected to produce relative species abundances that resemble the initial conditions data (Table 6); and 2) others were determined using linear mixed effects models fit to the LandWeb study area (described below)

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

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

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

Table 7. Data sources used by Biomass borealDataPrep module.

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

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

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

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

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

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

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

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

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

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

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

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

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

6.5.2.4 VEGETATION MODEL (LANDR BIOMASS) MODULE

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

6.5.2.5 BIOMASS_CORE MODULE

This module provided the core vegetation dynamics, simulating vegetation growth and mortality processes. The functions that determine growth and mortality were unchanged from LANDIS-II. Growth and mortality dynamics were simulated in 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., from the previous year) increased the available growing space. Competition occurred when a stand contained more than one species-age cohort.

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

6.5.2.6 Biomass_regeneration Module

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

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

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

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

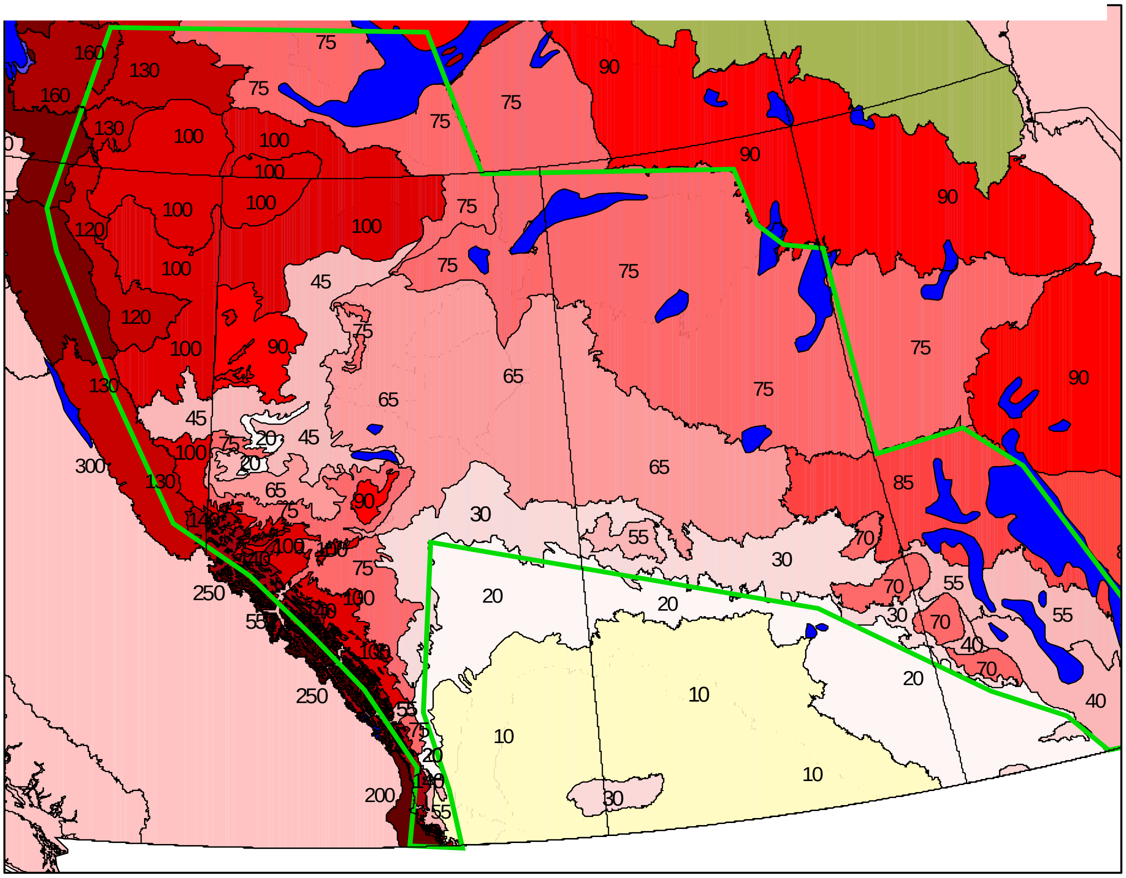
6.5.2.7 Fire model Module

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

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

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

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



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

Table 9. Data sources used by Landmine fire module.

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

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

6.5.2.8 LandWeb_output Module

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

6.5.2.9 timeSinceFire Module

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

6.5.2.10 Post-processing

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

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

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

6.5.3 RUNNING THE MODEL

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

6.6 VALIDATION

6.6.1 VEGETATION DYNAMICS

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

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

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

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

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

6) The resolution (i.e., pixel size) of the model was too coarse to capture the scale at which the relevant dynamics (of mortality, forest dynamics, and succession) occur.
7) The succession module was not calibrated to properly reflect the ecological diversity across the larger LandWeb study area.

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

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

processes, and thus a higher level of trust. What is the impact of parameter three (of 20+) on the outcome? What is the impact of not including parameter X, or getting it “right”? It is easier to be confident that individual model parameters are functioning as expected than it is to be confident that the various parameters fit together to create robust results.

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

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

7.0 RESULTS

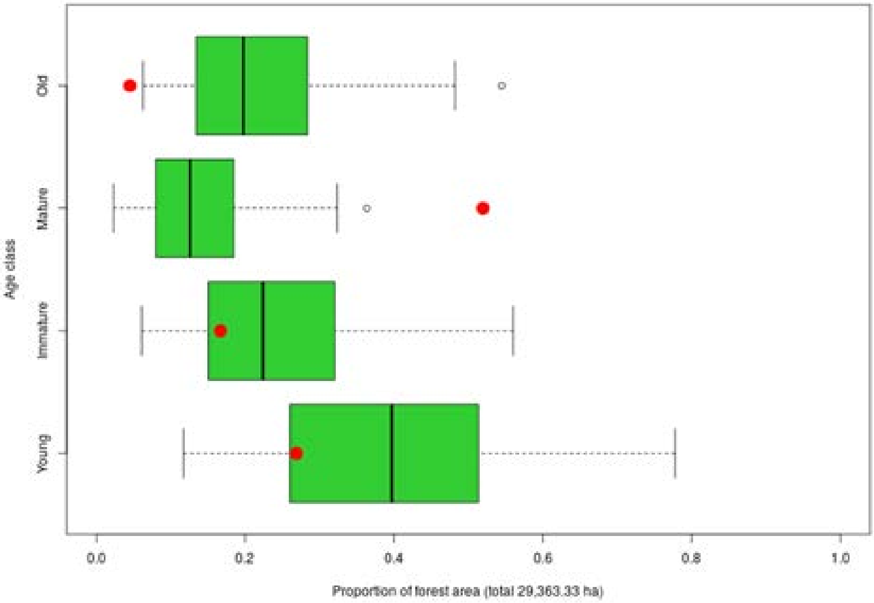
A.M. Chubaty, E.J.B. McIntire, and D.W. Andison

The results presented in this section include both non-spatial and spatial model output.

7.1 NON-SPATIAL RESULTS

The non-spatial results from the NRV modelling results are presented as *box and whisker plots (Figure 8)*. Box and whisker plots divide dozens, hundreds, or thousands of measurements into four evenly spaced groups (quartiles), each one representing 25% of the total number of measurements. For example, if the observations of the metric of concern were 2, 3, 4, 5, 9, 11, 16, 23, 25, 26, 27, 30, 40, 50, 70, and 100, the first quartile would be 2–7, the second 7–24, the third 24–35, and the fourth 35–100. The 50th percentile is the median. In Figure 8, the first quartile is the 'whisker' dotted line on the left, the second quartile is the green box left of the black vertical line (median), the third quartile is the green box on the right, and the fourth quartile is the (dotted line) whisker on the right. Note also in Figure 8 there are small open circles. These are known as *outliers* because they are significantly higher or lower than the rest of the data.

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

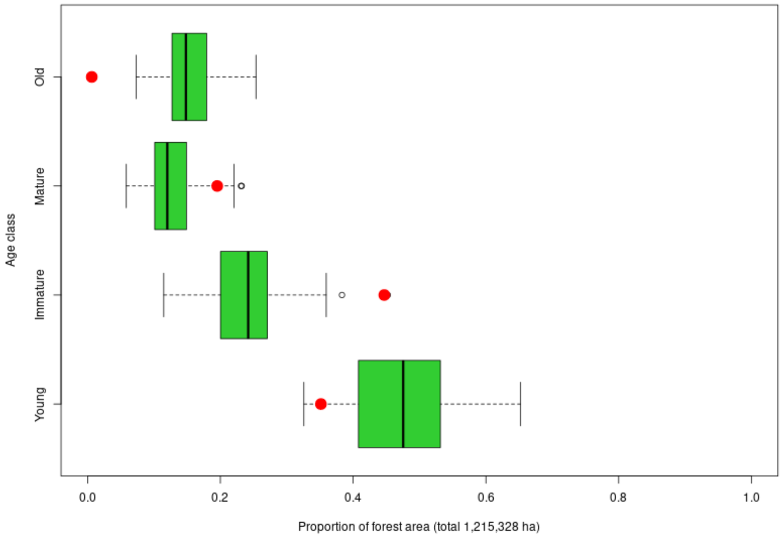


Box and whisker plots not only simplify output into a more visually intuitive form, but also allow simultaneous viewing of all seral stages. For example, each set of four quartiles represents all four seral-stages of a specific vegetation type. The associated area (ha) of the vegetation type is shown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

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

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

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



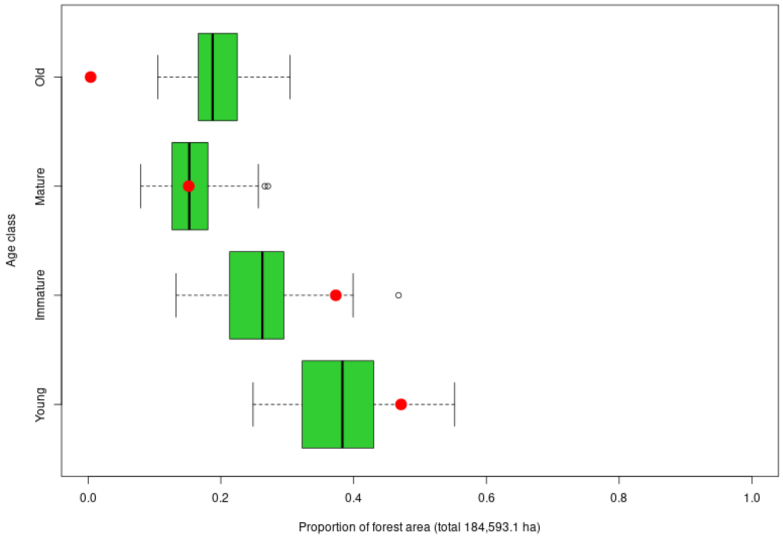
The first thing to note is that the amount of young (<40 years) forests across the FMA area ranged historically from 33–65%, with a median of 48%. This is among the highest levels of young forest observed across the entire LandWeb study area, and is a function of very frequent historical fire activity (i.e., LTFC of 55–65 years).

Thus, while young forest accounts for more than a third of all forest in the study area today, and technically within NRV, it represents only at the 2nd percentile (i.e., was only observed 20 times in the last thousand years). Immature forest levels currently account for 45% of all forest, which is well beyond anything observed historically from modelling (Figure 9). Mature forest levels (20%) are currently within NRV, but this time on the extreme upper end (i.e., the 98th percentile). Finally, the 1% currently observed as old forest (>120 years of age) is well below the pre-industrial estimates made by our modelling.

7.1.1 MAJOR VEGETATION TYPES

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

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



The 47% of young stands currently observed in pine-dominated forests on the study area are on the high end, but well within NRV. Similarly, the 37% of pine forest in the immature seral-stage are within, but very close to the upper end of NRV. Mature pine forest currently sits at the pre-industrial median, and old pine forest levels are well below the lower threshold of NRV from modelling (Figure 10).

Current levels of black spruce forest also deviate from NRV on the study area, but somewhat differently so than that of pine. The 36% in young black spruce is at the very low end of NRV, and the 44% of immature forest is more than 10% beyond the upper boundary of NRV. Mature forest levels are on the upper end of, but within NRV. As noted previously, the current amount of old black spruce forest (1%) is well below anything observed historically according to modelling (Figure 11).

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

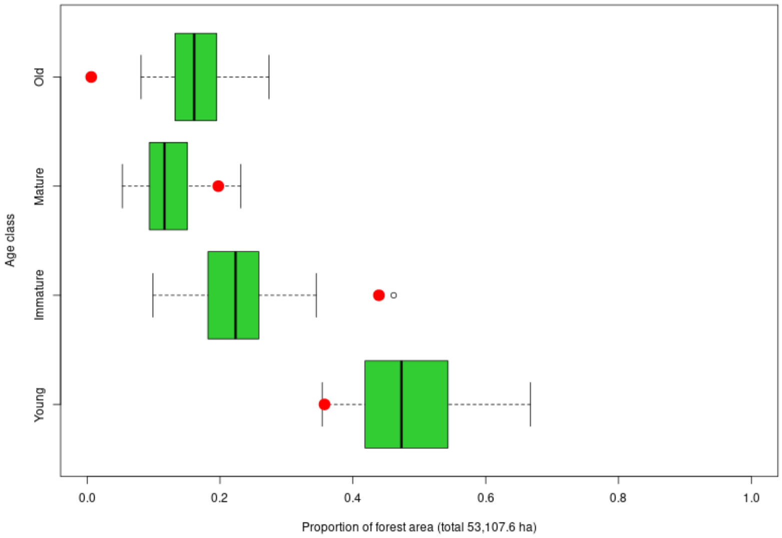
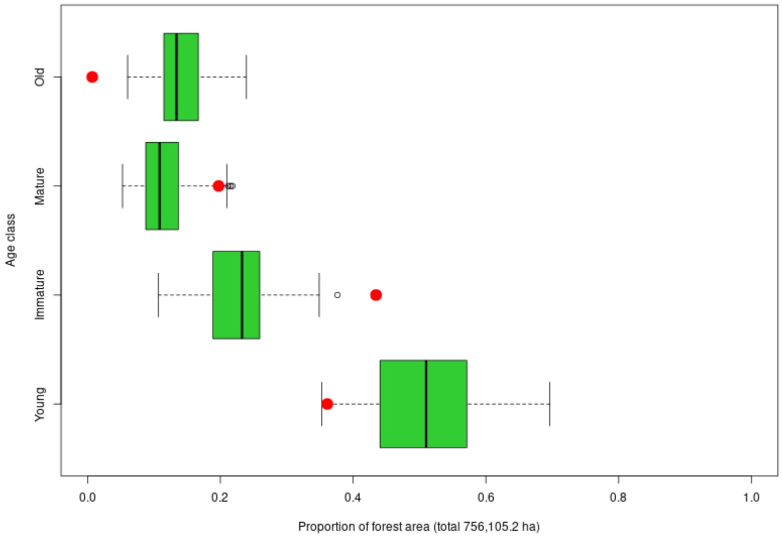


Figure 12. Historical ranges (box plot) and current levels (red dot) of mixedwood forest on the Mistik Management FMA



Current levels of mixedwood forest in the study area are almost all at or beyond NRV thresholds. Young forest levels are at the lower boundary of NRV, immature forest levels far beyond the upper boundaries of NRV, and old forest levels are well below the lower boundaries of NRV. While mature forest levels today are technically within NRV, it represents the 96th percentile (Figure 12).

Young white spruce forest levels (38%) are well within NRV and mature forest levels (19%) are within, but on the high end of NRV (Figure 13). In contrast, immature white spruce forest (41%) is just beyond the upper boundary of NRV, and the 2% old white spruce is well below the lower boundary of NRV (Figure 13).

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

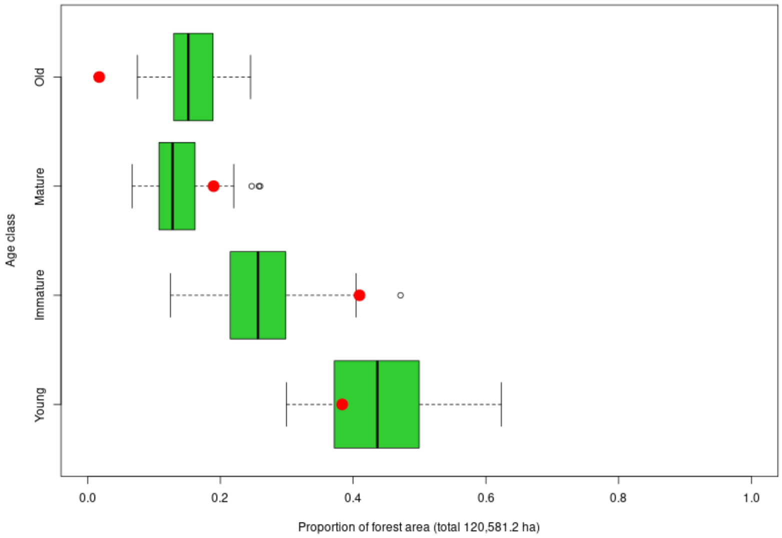
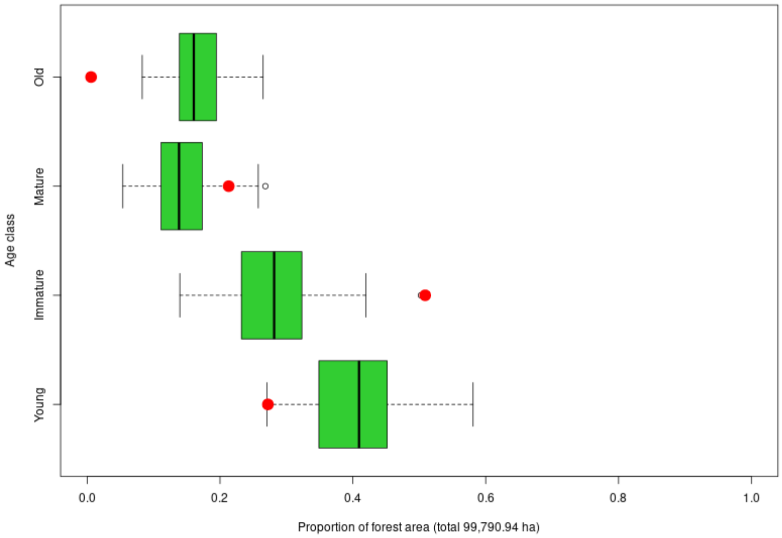


Figure 14. Historical ranges (box plot) and current levels (red dot) of deciduous forest on the Mistik Management FMA



Current levels of deciduous forest on the Mistik Management FMA are all near or beyond NRV. Old and young deciduous forest levels are either at or below the lower boundary of NRV. The majority (51%) of the current deciduous forest on the study area is immature, which is well above the 28% median of NRV. Current levels of mature deciduous forest are within, but very close to the upper NRV threshold (Figure 14).

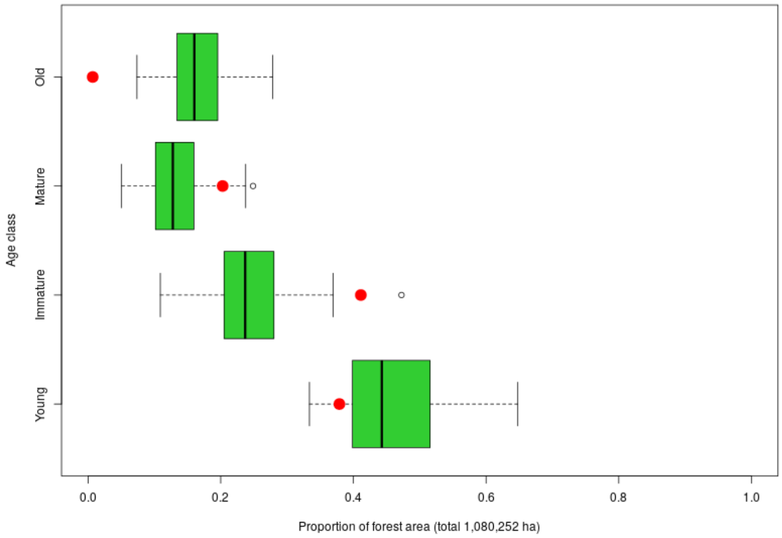
7.1.2 ECOLOGICAL NATURAL SUBREGIONS

All but 1% of the Mistik Management FMA includes the Mid-Boreal Uplands. The 26,000 ha in the Boreal Transition is not nearly large enough to report on relative to landscape-scale NRV.

7.1.3 WOODLAND CARIBOU RANGES

The Mistik Management FMA area includes a part of one woodland caribou range in Saskatchewan: the Boreal Plains.

Figure 15. Historical ranges (box plot) and current levels (red dot) for the Boreal Plains Caribou Range within the Mistik FMA.



The current level of young forest (i.e., <40 years old) within the Mistik Management FMA portion of the Boreal Plains range is 38% (Figure 15), which is just above the 35% maximum suggested (Environment Canada 2012). However, note that the 35% upper threshold of young forest was exceeded almost 90% of the time historically. In other words, it is unlikely that this landscape ever supported caribou according to current federal habitat guidelines.

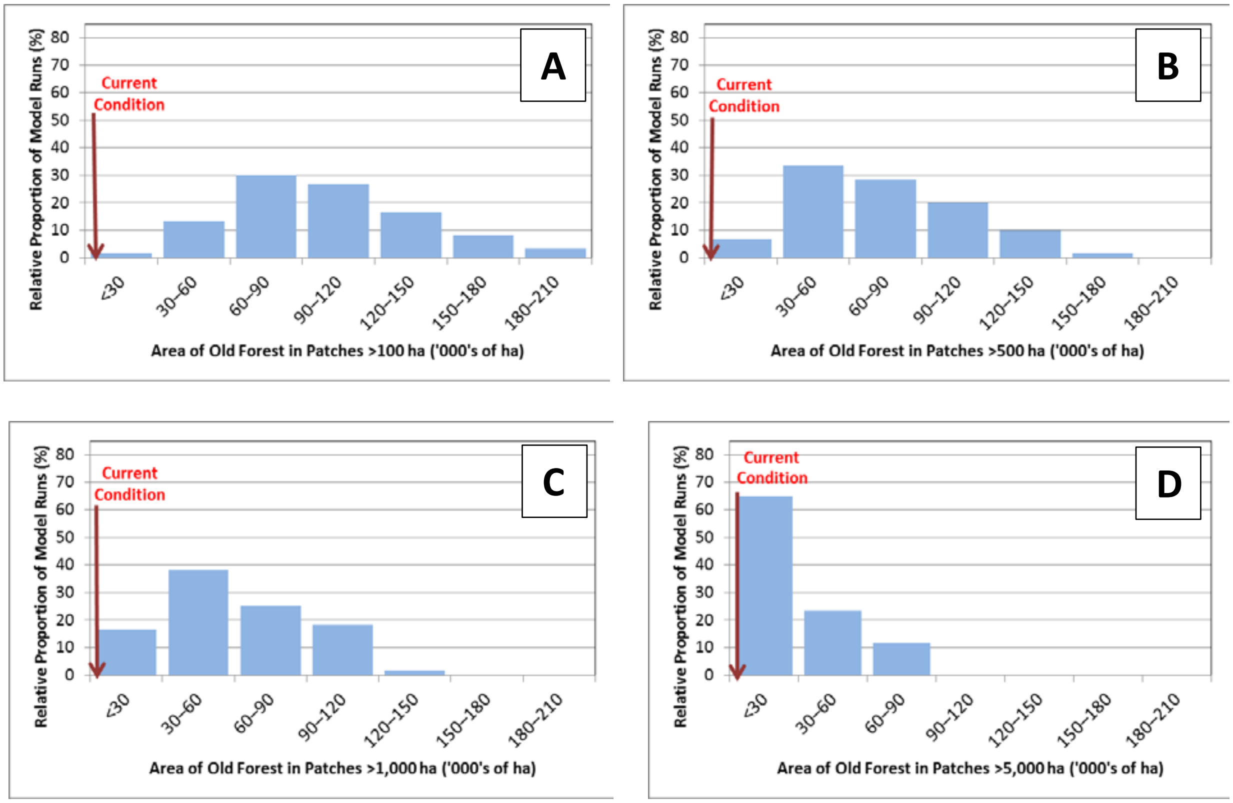
As previously noted, immature forest levels are currently far above NRV, old forest levels far below, and mature forest levels are within, but on the high end of NRV (Figure 15).

7.2 SPATIAL RESULTS

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

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 2600 and 199,000 ha historically compared to the 2200 ha observed today (Figure 16A). The area in old forest patches >500 ha historically ranged between 12,500 and 158,000 ha compared to zero ha today (Figure 16B). The pre-industrial area of old forest patches >1000 ha ranged from 7500 to 140,000 ha, compared to zero ha today (Figure 16C). Lastly, there were historically between zero and 82,000 ha in large old forest patches >5000 ha on the Mistik Management FMA, compared to zero ha today (Figure 16D).

Figure 16. NRV (blue bars) and current condition (red arrow) of the area in old forest patch sizes on the Mistik Management FMA area. Top left (A) is all old forest patches >100 ha. Top right (B) is old forest patches >500 ha. Bottom left (C) is all old forest patches >1000 ha and lower right all old forest patches >5000 ha.



8.0 DISCUSSION

D.W. Andison

8.1 OVERALL PATTERNS

The Mistik Management FMA area is currently unbalanced with respect to overall seral-stage distributions. There is too little old (and to a lesser degree young) forest, and too much immature and mature forest relative to NRV.

One possible explanation for the observed low levels of young forest is a regular, negative bias in forest inventories. Once a stand is harvested, it is often not assigned an age until it achieves some minimal forest "recovery" standard, which can take several years. In other words, at any given time, the level of young forest is likely under-estimated — meaning the young forest "red dots" are actually further to the right.

A more complex explanation of the lack of young forest involves the relationship between humans and the study area. This area has been under intensive fire control protection for several decades. Yet, fire records suggest that a gross area of 600,000 ha of the FMA area burned in the last 40 years. After accounting for the likely area in fire residuals, about 20% of the young seral stage is due to fire activity. Most of the rest is due to other natural disturbance agents (see ahead) plus forest harvesting. In terms of harvesting, the maximum rate of harvesting in Saskatchewan is determined based on the principle of *sustainable yield* (Monserud 2003). In practice, this means the harvest levels should never exceed the expected growth over a given time period, much like the concept of withdrawing only the interest from a bank account but never the principle. Thus, under ideal conditions, a landscape on which the maximum allowable harvesting occurs will maintain a relatively constant age-class distribution over time. However, under realistic conditions, that rarely happens. First, as noted above, despite our best efforts, wildfire and other natural disturbance agents remain active, also contributing to the amount of young forest (in this case for more than half of the current level of young forest). Second, rarely, if ever, are the maximum allowable harvest levels realized. And third, the calculation of maximum allowable harvest levels is based only on that part of the forest that is capable of being harvested at some point in the future, known otherwise as the *contributing* or *active* land base. In the Mistik study area, the active land base area accounts for only about 44% of the FMA area. This means that on the study area disturbance levels from timber management are, at most, less than half of that experienced in the pre-industrial era. So, in summary, young forest levels are on the low end, but still within NRV only due to a combination of equal parts harvesting activity, and unplanned natural disturbance activity. This exposes a significant challenge on this landscape; without future (potentially risky and costly) unplanned fire activity, the amount of young forest will move below the lower end of NRV.

The NRV - current condition gap for immature forest is significant. The list of possible explanations is limited. From a merchantability perspective, harvesting activity in stands that are now 40–80 years of age would only have begun about 10 years ago, and likely only then on a relatively small scale. At the same time, this seral-stage would have had the benefit of wildfire protection, although on a more limited scale than that of today. So the large amount of immature forest is a combination of low levels of both fire and harvesting.

Mature forest levels are currently within, but on the high end of NRV. This may be due in part to relatively high between 1900 and 1940. Fire management activities were either absent, unsophisticated, or highly spatially restricted prior to 1940. Although this pre-dates provincial fire records, a fire history mapping exercise on about 100,000 ha of the southern end of the FMA area found multiple fire years between 1900 and 1940 (Andison et al. 2003). The high levels of mature forest may also be due to the preference of harvesting to older stands.

Another possible explanation for the high amount of mature forest is that the forest inventory data used to generate the “red dot” current condition ages are biased. The original, intended purpose of a forest inventory is to provide relevant information to forest management planners and managers as regards timber values. From a timber management perspective, once a stand is deemed to be merchantable the precision of its age becomes less important. In terms of process, it also becomes much more challenging to differentiate the difference on aerial photos between a 100 year old stand and a 130 year old stand. Moreover, although current forest inventory standards include ground-truthing, the aging methods are inadequate to represent the complex dynamics of older and/or multi-aged stands. In fact, a local stand origin study showed that the chances of picking up the origin date of the last stand-replacing fire decreases with age (Andison et al. 2003, Andison 1999). This means that some portion of the forest reported today in the study area in the mature seral-stage may be older.

The NRV-current condition gap for old forest is the most significant, and there are several possible explanations. First, forest harvesting by definition only occurs on merchantable forest, which in Saskatchewan conservatively starts at 60–80 years of age, depending on location and site. The degree to which harvesting may have focused on the very oldest forest available is unknown, and beyond the scope of this study. However, this hypothesis alone does not explain the gap. Recall that harvesting activities only occur on about 44% of the landscape, and forest protection (from wildfire) occurs on 100%. So the passive forest area should have natural levels (i.e., within NRV) of old forest — if not higher, because of fire control.

Thus, the second possible explanation for the noted NRV-current condition gap is that some or all of the natural disturbance vectors favour old forest. An increase in flammability associated with stand age is not only well documented, but built right into the Canadian Fire Behaviour Prediction System. The age-dependent increase in fire risk is largely due to the increase in both vertical and horizontal fuel continuity, rather than biomass accumulation. Other sources of natural disturbance in the study area include spruce budworm, jack pine budworm, and forest tent caterpillar, although Dwarf Mistletoe, larch beetle, aspen canker, aspen dieback, and aspen heart rot are also active (Government of Saskatchewan 2019, Volney and Fleming 2000). Although most of these do not directly lead to mortality, mortality risk generally increases with age as well as overlapping vectors (Bauce et al. 1994, Volney 1998, Brandt et al. 2003). Aspen dieback is of particular concern for the study area given its proximity to the southern boundary of the forest (Frey et al. 2004), most infamously so in the Bronson (Hogg 2001). These incidents are also significantly linked with stand age.

The final possibility is that the forest inventory data used to generate current condition “red dot” current condition ages are biased. As described above, it is possible that some portion of what forest inventories today designate as mature, are actually old. However, field sampling from a local stand origin mapping exercise found very little evidence of forest stands >120 years of age (Andison et al. 2003).

The spatial results in this study area are largely a reflection of the very low levels of old forest. Patch sizes of old forest are a product of decades of overlapping disturbance activity. Thus, regardless of the reason(s), a very low level of old forest on any given landscape will always translate into low levels of old forest clustering. So that fact that the old forest patch sizes today are on the very low end of NRV from modelling is entirely predictable. Unfortunately, this also means that the results are unable to offer any further insights. The only way to dive deeper into this metric is to parse the impact of the various activities in terms of current condition for the study area. For example, 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. Thus, a *relative* evaluation of old forest patch sizes is possible. Another possibility is to use mature forest patch sizes instead.

8.2 POSSIBLE SOURCES OF ERROR IN THE MODEL

One of the most widely known quotes about modelling is from George Box: “*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 range of possibilities is 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 long-term fire cycle (LTFC) is 16%, compared to 20% for a LTFC of 75 years, and 26% for a landscape with a LTFC of 90 years.

The process of identifying pre-industrial LTFCs in the study area was thorough and extensive, including a) an informal review of historical local records, b) a literature review, c) a two-day expert workshop, and, d) four iterations of a LTFC map from anonymous expert opinion over four years (see Andison 2019). In the end, the LTFC map represents the best available science; although the confidence level of the final LTFCs varies by region. The confidence levels of LTFCs in this particular part of the LandWeb study area were higher than average, and raised no significant red flags among the experts (Andison 2019). Having said that, one of the advantages of a spatial modelling exercise is the ability to test input assumptions (including LTFCs) *via* a sensitivity analysis. Aptly named, a sensitivity analysis allows one to test the impact of model output on different input assumptions, which, in this case would be changing the LTFC numbers by plus or minus 5, 10, or 20 years on either side of those shown in Figure 2. This addresses the question; "*if we are wrong about LTFCs, what would the impact be on our conclusions?*" In this case, this would be advisable to at least allow for an evaluation of how sensitive seral-stage NRV levels are to LTFCs.

Another possible source of error could be the under-representation of low and moderate severity fires in the model. As with every other landscape-scale model today, the fire spread module in LandWeb captures and represents severity in a simplistic, binary fashion: Either a pixel burns completely or not at all. However, evidence suggests that some percentage of historical fires left behind significant areas of partially burned forest (Andison 2004). This could influence succession dynamics in a number of ways. First, as residual forest levels increase, the "regeneration" components of the LANDIS succession model are less relevant, based on time-since-fire alone. For example, a 70 year old forest that experiences only 30% mortality from a fire will clearly be functioning as a sexually mature forest type, with a shade tolerant and re-sprouting understorey. Second, the introduction of low to moderate severity fires challenges, and suggests expanding on, simple definitions of a seral-stage to capture more complex forest age structures such as definitions of "old growth". Partial mortality is also likely to complicate the definition of habitat types (Amoroso et al. 2011), perhaps most notably as it relates to caribou.

The last potential sources of error in the results are the current condition estimates. With reference to current condition for the non-spatial results (i.e., the red dots), ages were taken from the most recent forest inventory. As discussed above, while SFVI captures age data for every forest polygon, identifying the exact stand age is not a high priority. Inventory age estimates of older stands decreases in accuracy, and increases in bias (Andison 1999a, 1999b).

There are two challenges inherent in the calculation of current condition for patch sizes. The first is tracking, classifying, and dating each disturbance feature. As with age data, SFVI does not prioritize capturing details on all types of these data. Another challenge for the current condition estimate of patch sizes is more daunting: How to integrate and compare the impacts of forest edges of different sources and ages? For example, if/how do we differentiate edges along highways from a bush road, a large, new seismic line, or a small and/or very old seismic line? For this study, any and all disturbance features were used, but this could easily be augmented by a sensitivity analysis that creates several alternative "edge" scenarios.

8.3 IMPLICATIONS

In theory, a landscape that is close to, or has already shifted beyond NRV creates greater risks to the sustainable flow of goods and services, and is less resilient to the impacts of future perturbations (Christensen et al. 1996, Hunter 1996). The issue in this case is an age-class imbalance; not enough young or old forest, and too much immature and mature forest.

Diversity is generally partitioned into two parts; 1) *Richness* (the absolute number of ecological elements), and 2) *Evenness* (the relative proportion of each element (DeJong 1975)). In this case, the number of seral elements (i.e., richness) has not changed relative to NRV, but the current proportion of each (i.e., evenness) has, and in some cases dramatically so. At landscape scales, species and ecosystem functions have evolved over thousands of years, relying on a natural range of proportions of habitat types over time and space. EBM theory suggests that pushing a landscape system (too far and for too long) beyond this natural range is likely to create some unexpected, mostly negative outcomes for the resident species and services (Pickett et al. 1992).

In this case, there are both over and under-represented habitat types on the Mistik FMA area relative to NRV. The under-represented seral-stages include both old and young forest. Although the ecological value of old forest is well recognized and documented (e.g., Goulden et al. 2011), less well recognized is the ecological value of young forest (Kuuluvainen and Gauthier 2018). Young forest provides critical habitat and environmental conditions, and the soil nutrient profiles necessary for the existence of a large number of boreal species 1–5 years after wildfire (e.g., Coop et al. 2010, Yeager et al. 2005). Landscapes with proportions of young forest below those experienced historically are thus likely to be less health and resilient, and unlikely to provide the full range of goods and services we expect.

9.0 RECOMMENDATIONS

D.W. Andison

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

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

2) **Update the current condition "red dots".** It is not clear if or to what degree the estimates reflect the current reality – including recently burned or harvested areas.
3) **Re-evaluate and openly share 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 disturbance-dependent ecosystem. This means one of the ultimate measures of a healthy ecosystem (and thus sustainability) is the *quality* of disturbance activities, not the *existence* of them.
4) **Begin efforts to integrate forest and fire management**. The only reason the study area is not much further beyond NRV is the large area of wildfire in the last 40 years – despite intensive, sophisticated, and coordinated fire control efforts. Going forward, the best way to avoid this as a future scenario is to coordinate.
5) **Do a sensitively analyses with different LTFCs.** The possibility remains that the LTFCs used in the modelling are wrong. While most agreed the ones used for this exercise were close to the historical reality, the experts were split on this one: half thought they were longer, and half shorter – and the other half thought they were right!
6) **Support ongoing research and model upgrades**. In this case, there are two relevant priorities:
    a. The observed current and NRV patterns and unanswered questions associated with old forest levels are important to address. The results suggest that old forest levels are currently well below the lower end of NRV, but there are a number of potentially mitigating circumstances and caveats, any one of which could change the results significantly. Each one can be tested, and estimates / modelling adapted.
    b. Given the high, natural frequency of wildfire, and the observed moderate to high level of fire remnants in historical fires, the prevalence and role of low to moderate severity fires should be explored further. Multiple overlapping fires over a few decades are a common occurrence here, and may compromise the concept of age-defined seral-stages. This does not have to be LandWeb.
7) **Finalize LandWeb testing and validation.** The way in which LandWeb converts stand-types right now is unrealistic. 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 should be a priority. Although the answer(s) may not impact the findings from this study, this will help make the LandWeb model more valuable and defendable as a tool going forward.

LITERATURE CITED

Amoroso, M.M., Daniels, L.D., Bataineh, M. and Andison, D.W. 2011. Evidence of mixed-severity fires in the foothills of the Rocky Mountains of west-central Alberta, Canada. Forest Ecology and Management 262: 2240–2249.

Andison, D.W. 2019. Pre-industrial fire regimes of the western boreal forests of Canada. fRI Research, Hinton, Alberta. August 12, 2019. 49p.

Andison, D.W. 2012. The influence of wildfire boundary delineation on our understanding of burning patterns in the Alberta foothills. Canadian Journal of Forest Research 42: 1253–1263.

Andison, D.W. 2004. Island remnants on foothills and mountain landscapes of Alberta: Part II on residuals. Foothills Model Forest, Hinton Alberta. 41p.

Andison, D.W. 1999a. Assessing forest age data in foothills and mountain landscapes of Alberta: Laying the groundwork for natural pattern research. Disturbance Ecology Report Series #1l Foothills Model Forest, Hinton, Alberta. Oct. 1999.

Andison, D.W. 1999b. Validating forest age data on the Mistik FMLA: Laying the groundwork for natural pattern research. Bandaloop Landscape Ecosystem Services. Coal Creek Canyon, Colorado. Dec. 1999.

Andison, D.W. 1998. Temporal patterns of age-class distribution on the foothills landscapes in Alberta. Ecography 21: 543–550. https://doi.org/10.1111/j.1600-0587.1998.tb00446.x.

Andison, D.W. 1996. Managing for landscape patterns in the sub-boreal forests of British Columbia. PhD thesis. UBC Forestry. 203p. https://open.library.ubc.ca/cIRcle/collections/ubctheses/831/items/1.0075275.

Andison, D.W. and K. McCleary. 2014. Detecting regional differences in within-wildfire burn patterns in western boreal Canada. The Forestry Chronicle. 90: 59–69.

Andison, D.W., M.P. Rogeau, P.L. Marshall, and P.M. LeMay. 2003. Comparing Stand Origin Ages with Forest Inventory Ages on a Boreal Mixedwood Landscape: Pilot Study Report. Bandaloop Landscape-Ecosystem Services. March 31, 2003. 31p.

Barros, C., Y. Luo, E.J.B. McIntire, A.M. Chubaty, D.W. Andison and S.G. Cumming (in prep). Land-R: a seamless union between landscape modelling and model parameterisation. To be submitted to Methods in Ecology and Evolution.

Bauce, E. M. Crepin, and N. Carisey. 1994. Spruce budworm growth, development and food utilization on young and old balsam fir trees. Oecologia. 97: 499-507.

Beaudoin, A., P.Y. Bernier, L. Guindon, P. Villemaire, X.J. Guo, G. Stinson, T. Bergeron, S. Magnussen, and R. J. Hall. 2014. Mapping Attributes of Canada's Forests at Moderate Resolution through KNN and MODIS Imagery. Canadian Journal of Forest Research 44: 521–532. https://doi.org/10.1139/cjfr-2013-0401.

Beverly, J.L., and N. McLoughlin. 2019. Burn probability simulation and subsequent wildland fire activity in Alberta, Canada – Implications for risk assessment and strategic planning. Forest Ecology and Management 451: 117490. https://doi.org/10.1016/j.foreco.2019.117490.

Booth, D.L., D.W.K. Boulter, D.J. Neave, A.A. Rotherham, D.A. Welsh. 1992. Natural forest landscape management: a strategy for Canada. (unpublished draft). 14 pp.

Brandt, J.P., H.F. Cerezke, K.I. Mallett, W.J.A. Volney, and J.D. Weber. 2003. Factors affecting trembling aspen (Populous tremuloides Michx.) health in the boreal forest of Alberta, Saskatchewan, and Manitoba, Canada. Forest Ecology and Management. 178(3): 287-300.

Christensen, N.L., A.M. Bartuska, J.J. Brown, S. Carpenter, C. D'Antonio, R. Francis, J.F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner, and R.G. Woodmansee. 1996. The report of the ecological society of America Committee on the scientific basis for ecosystem management. Ecological Applications 6: 665–691.

Chubaty, A.M. and E.J.B. McIntire. 2018. SpaDES: Develop and Run Spatially Explicit Discrete Event Simulation Models. http://cran.r-project.org/package=SpaDES.

Chubaty, A.M. 2019a. SpaDES.Core: Core Utilities for Developing and Running Spatially Explicit Discrete Event Simulation Models. http://cran.r-project.org/package=SpaDES.core.

Chubaty, A.M. 2019b. SpaDES.Tools: Additional Tools for Developing Spatially Explicit Discrete Event Simulation (SpaDES) Models. http://cran.r-project.org/package=SpaDES.tools.

Clarke, K.C., J.A. Brass, and P.J. Riggan. 1994. A cellular-automaton model of wildfire propagation and extinction. Photogrammetric Engineering and Remote Sensing 60: 1355–1367.

Coop, J.D., R.T. Massatti, and A.W. Schoettle. 2010. Subalpine vegetation pattern three decades after stand-replacing fire: effects of landscape context and topography on plant community composition, tree regeneration, and diversity. Journal of Vegetation Science 21: 472–487.

Cosco, J.A. 2011. Common Attribute Schema (CAS) for Forest Inventories Across Canada. Timberline Natural Resource Group for Boreal Avian Modelling Project and Canadian BEACONs Project. http://www.borealbirds.ca/files/CAS_Document_Final_Mar_2010_ALL_APPENDICES.pdf.

Davis, W. 1993. The global implications of biodiversity. M.A. Fenger et al. (eds.), Our Living Legacy. Proc. of a Symp. on Biological Diversity. Victoria, BC. pp. 23–46.

DeJong, T.M. 1975. A comparison of three diversity indices based on their component of richness and evenness. Oikos 26: 222–227.

Environment Canada. 2012. Recovery strategy for the Woodland Caribou (*Rangifer tarandus caribou*), Boreal population, in Canada. Species at risk act recovery strategy series. Environment Canada, Ottawa, Ontario. 138pp. http://books.scholarsportal.info/viewdoc.html?id=/ebooks/ebooks0/gibson_cppc/2015-03-25/1/11009432.

Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems, or landscapes? Ecological Applications 3: 202–205.

Frey, B.R., V.J. Lieffers, E.H. Hogg, and S.M. Landhusser. 2004. Predicting landscape patterns of aspen dieback: Mechanisms and knowledge gaps. Canadian Journal of Forest Research. 34(7). https://doi.org/10.1139/x04-062

Goulden, M.L., A.M.S. McMillan, G.C. Winton, A.V. Rocha, K.K. Manies, J.W. Harden, and B.P. Bond-Lamberty. 2011. Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. Global Change Biology 17: 855–871. https://doi.org/10.1111/j.1365-2486.2010.02274.x

Government of Saskatchewan. 2019. State of the Forest Report. Saskatchewan, Canada. 51p.

Grumbine, E.R. 1994. What is ecosystem management? Conservation Biology 8: 27–38.

Haag, D. and M. Kaupenjohann 2001. Parameters, predictions, post-normal science, and the precautionary principle — a roadmap for modelling decision-making. Ecological Modelling 144:45–60.

Hammah, R.E., and J.H., Curran. 2009. It is better to be approximately right than precisely wrong: Why simple models work in mining geomechanics. Presented at: the 43rd US Rock Mechanics Symposium and 4th US-Canada Rock Mechanics Symposium, Asheville, NC. June 28 – July 1, 2009.

Hogg, E.H. 2001. Modeling aspen responses to climate warming and insect defoliation in western Canada. In: Sustaining aspen in western landscapes: Symposium Proceedings. June 13-15, 2000. USDA Forest Service Proceedings RMRS-P-18. Pp 325-338.

Hunter, M. 1996. Benchmarks for managing ecosystems: Are human activities natural? Conservation Biology 10: 695–697.

Johnson, E.A. 1992. Fire and vegetation dynamics: Studies from the North American Boreal Forest. Cambridge U. Press, Great Britain. 129pp.

Krueger, T.T. Page, K. Hubacek, L. Smith, and K. Hiscock. 2012. The role of expert opinion in environmental modelling. Environmental Modelling and Software. 36: 4–18.

Kuuluvainen, T., and S. Gauthier. 2018. Young and old forest in the boreal: Critical stages of ecosystem dynamics and management under global change. Forest Ecosystems 5: 26. https://doi.org/10.1186/s40663-018-0142-2

Latifovic, R., and D. Pouliot. 2005. multi-temporal land cover mapping for Canada: methodology and products. Canadian Journal of Remote Sensing 31: 347–63. https://doi.org/10.5589/m05-019.

Long, J.N. 2009. Emulating natural disturbance regimes as a basis for forest management: A North American view. Forest Ecology and Management 257: 1868–1873.

McIntire, E.J.B., and A.M. Chubaty. 2019. Reproducible: A Set of Tools That Enhance Reproducibility Beyond Package Management. Canadian Forestry Service, Victoria, BC.

Monserud, R.A., 2003. Evaluating forest models in a sustainable forest management context. FBMIS, 1: 35–47. http://www.fbmis.info/A/3_1_MonserudR_1

Noble, I.R., and R.O. Slatyer. 1980. The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43: 5–21.

Payette, S. 1993. Fire as a controlling process in North American boreal forest. In: West, D.C., H.H. Shugart, and D.B. Botkin (eds.), Forest Succession: Concepts and Applications. Springer-Verlag, New York. pp. 144–169.

Pickell, P.D. D.W. Andison and N.C. Coops. 2013. Characterization of anthropogenic disturbance patterns in the mixedwood boreal forest of Alberta, Canada. Forest Ecology and Management 304: 243–253.

Pickell, P.D., D.W. Andison, N.C. Coops, S.E. Gergel, and P.L. Marshall. 2015. The spatial pattern of anthropogenic disturbance in the western Canadian boreal forest following oil and gas development. Canadian Journal of Forest Research 45: 732–743.

Pickell, P.D, and N.C. Coops. 2016. Development of Historical Forest Attribute Layers Using Landsat Time Series and KNN Imputation for the Western Canadian Boreal Forest. University of British Columbia, Vancouver, BC, Canada.

Pickett, S.T.A., Parker, V.T., and Fielder, P.L. 1992. The new paradigm in ecology: Implications for conservation biology above the species level. Jian, P.L. (Ed.). Conservation biology: The theory and practice of nature conservation, preservation, and management. pp. 65–88. Chapman and Hall, New York, NY.

R Core Team. 2018. R: A Language and Environment for Statistical Computing (version 3.5.2). Vienna, Austria: R Foundation for Statistical Computing. http://www.r-project.org/

Scheller, R.M., J.B. Domingo, B.R. Sturtevant, J.S. Williams, A. Rudy, E.J Gustafson, and D.J. Mladenoff. 2007. Design, Development, and Application of LANDIS-II, a Spatial Landscape Simulation Model with Flexible Temporal and Spatial Resolution. Ecological Modelling 201: 409–19. https://doi.org/10.1016/j.ecolmodel.2006.10.009.

Scheller, R.M, and B. Miranda. 2015. LANDIS-II Biomass Succession v3.2 Extension User Guide. User Guide. https://github.com/LANDIS-II-Foundation/Extension-Biomass-Succession/blob/master/docs/LANDIS-II%20Biomass%20Succession%20v3.2%20User%20Guide.docx.

Scheller, R.M, and D.J. Mladenoff. 2004. A Forest Growth and Biomass Module for a Landscape Simulation Model, LANDIS: Design, Validation, and Application. Ecological Modelling 180: 211–229. https://doi.org/10.1016/j.ecolmodel.2004.01.022.

Scheller, R.M., and D.J. Mladenoff. 2007. An Ecological Classification of Forest Landscape Simulation Models: Tools and Strategies for Understanding Broad-Scale Forested Ecosystems. Landscape Ecology 22: 491–505. https://doi.org/10.1007/s10980-006-9048-4.

Statistics Canada. 2018. Ecological Land Classification, 2017. http://publications.gc.ca/collections/collection_2018/statcan/12-607-x/12-607-x2018001-eng.pdf.

Stringham, T.K., W.C. Krueger, and P.L. Shaver. 2003. State and transition modelling: An ecological process approach. Journal of Range Management 56: 106–113. http://doi.org/10.2307/4003893.

Turner, M.G., and V.H. Dale. 1991. Modelling landscape disturbance. In: Turner, M.G. and R.H. Gardner (eds), Quantitative methods in landscape ecology. Ecol. Studies 82, Springer-Verlag. pp. 322–351.

Volney, W.J.A. 1998. Ten-year mortality following a jack pine budworm outbreak in Saskatchewan. Canadian Journal of Forest Research. 28(12). http://doi/org/10.1139/x98-147

Volney, W.J.A., and R.A. Fleming. 2000. Climate change and impacts of boreal forest insects. Agriculture, Ecosystems and Environment. 82:283-294.

Wilken, E.B. 1986. Terrestrial Ecozones of Canada. Ecological Land Classification No. 19. Environment Canada, Hull, Quebec. 26pp.

Yeager, C.M., D.E. Northup, C.C. Grow, S.M. Barns, C.R. Kuske. 2005. Changes in nitrogen-fixing and ammonia-oxidizing bacterial communities in soil of a mixed conifer forest after wildfire. Applied and Environmental Microbiology 71: 2713–2722.

APPENDIX A: TABULAR QUARTILE RESULTS

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

Vegetation Type	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (Percentile)						
			MIN	12.5%	25%	50%	75%	87.5%	MAX
All species	Young	35	33	39	41	48	53	56	65
	Immature	45	11	17	20	24	27	30	36
	Mature	20	6	8	10	12	15	18	22
	Old	1	7	11	13	15	18	20	25
Black Spruce	Young	36	35	39	42	47	54	59	67
	Immature	44	10	16	18	22	26	29	34
	Mature	20	5	8	9	12	15	17	23
	Old	1	8	11	13	16	20	21	27
Deciduous	Young	27	27	32	35	41	45	49	58
	Immature	51	14	21	23	28	32	35	42
	Mature	21	5	10	11	14	17	21	26
	Old	1	8	11	14	16	19	22	26
Mixedwood	Young	36	35	42	44	51	57	60	70
	Immature	43	11	15	19	23	26	29	35
	Mature	20	5	7	9	11	14	17	21
	Old	1	6	10	11	13	17	18	24
Pine	Young	47	25	30	32	38	43	48	55
	Immature	37	13	19	21	26	29	31	40
	Mature	15	8	11	13	15	18	22	26
	Old	0	11	15	17	19	22	25	30
White Spruce	Young	38	30	36	37	44	50	55	62
	Immature	41	12	19	21	26	30	33	40
	Mature	19	7	9	11	13	16	19	22
	Old	2	8	11	13	15	19	21	25

Table A2. Historical quartile and current range by caribou ranges on the Mistik Management FMA area.

Caribou Range	Age-Class	Current Condition (%)	Pre-Industrial Modelling Results (Percentile)						
			MIN	12.5%	25%	50%	75%	87.5%	MAX
SK Boreal Plains	Young	38	33	36	40	44	52	56	65
	Immature	41	11	17	21	24	28	31	37
	Mature	20	5	9	10	13	16	19	24
	Old	1	7	12	13	16	20	22	28