Timber and carbon geosimulation modelling platform

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Green Analytics, Inc.

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Preface:

The Alberta Biodiversity Monitoring Institute (ABMI) is an arm's-length, not-for-profit scientific organization. The primary goal of the ABMI is to provide relevant scientific information on the state of Alberta's biodiversity to support natural resource and land-use decision making in the province.

In the course of monitoring terrestrial and wetland ecosystems across the province, the ABMI has assembled a massive biodiversity database, developed reliable measurement protocols, and found innovative ways to summarize complex ecological information.

The ABMI undertakes focused projects to apply this capacity to specific management challenges, and demonstrate the value of the ABMI's long-term monitoring data to addressing these challenges. In some cases, these applied research projects also evaluate potential solutions to pressing management challenges. In doing so, the ABMI has extended its relevance beyond its original vision.

The ABMI continues to be guided by a core set of principles – we are independent, objective, credible, accessible, transparent and relevant.

This report was produced in support of the ABMI's Ecosystem Service Assessment project, which is developing systems to assess and map ecosystem services across Alberta to better understand how planning and management decisions affect the landscape and increase benefits to Albertans. "Ecosystem services" are the benefits provided by natural systems that contribute to our well-being and health. They support our basic needs like clean water, food, and raw materials for building, or they can be more intangible benefits like recreational opportunities and aesthetic value. Some ecosystem services have a clear, well-known economic value, but the value of most services is harder to calculate, though no less important. Given the essential role that ecosystem services play in our lives, it is important to map, measure, and value these services. Powered with this information, Albertans can make the best possible decisions about how to manage our landscape.

The views, statements, and conclusions expressed in this report are those of the author and should not be construed as conclusions or opinions of the ABMI. The ABMI is a value-neutral organization committed to the application of high quality science to natural resource management in Alberta.

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Timber and Carbon: Model Documentation

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1. Context

Ecosystem services are increasingly becoming a construct for policy makers, scientists and practitioners to conceptualize nature as a natural system within and foundational to a socio-economic system. The ecosystem services concept emphasizes the role that healthy ecosystems play in the sustainable provision of human well-being, economic development and poverty alleviation…"[1]

According to the Business for Social Responsibility Network there are five emerging global trends in ecosystem service related policy.[2]

- National governments are the world are exploring expansion of gross domestic product (GDP) measures to include natural capital
- Public sector exploration of ecosystem service valuation is on the rise
- Governments around the world are showing interest in attracting investment in ecosystem services
- Public sector funding research on ecosystem system is on the rise
- Engagement between public and private sectors on ecosystem services is limited but it has grown each year

As the importance and acceptance of the ecosystem service concept grows there is an increasing need to develop a science-based approach to defining and assessing ecosystem services. Turner and Daily (2008) argue that information at scales useful for decision makers on how people benefit from specific services is lacking, and that better integrated approaches are required for modelling, mapping and valuing ecosystem services.

ABMI and its consortium of collaborators in the Ecosystem Service Assessment for Environmental Innovation and Competitiveness project are advancing the capacity to conduct ecosystem service assessments in Alberta. This document contributes to the challenge of developing an integrated approach to model, map and assign value to ecosystem services in Alberta. This document and the subsequent sections describe an integrated model for timber and carbon provisioning.

[1] Turner, R. K. and Daily, G. C. (2008): The ecosystem services framework and natural capital conservation. Environmental & Resource Economics 39(1): 25-35.
[2] Business for Social Responsibility 2013. Global Public Sector Trends in Ecosystem Services, 2009-2012. Available online http://www.bsr.org/en/our-insights/report-view/global-public-sector-trends-in-ecosystem-services-2009-2012

1.1 Timber Production and Carbon Storage

Forest ecosystems play a vital role in sustaining human well-being and contributing to economic health in Alberta. Forest ecosystems provide direct and indirect economic output, jobs and an array of wood products that provide benefits to Albertans. Forest ecosystems are also home to vast stores of carbon. Globally, maintaining carbon stores and continuing to realize economic benefits from forests is a critical role for governments and forest managers, particularly as society continues to control runaway concentrations of greenhouse gas emissions (GHGs) in the atmosphere.

The Intergovernmental Panel on Climate Change's (IPCC) most recent comprehensive assessment of climate change science, its Fourth Assessment Report, clearly states that to avoid dangerous levels of climate change requires a 50% reduction in global greenhouse gas (GHG) emissions by 2050.[3] Climate change, land-use change and the world's forests are inextricably linked within the global carbon cycle as both a source of carbon emissions and a carbon sink.[4]

The timber and carbon geosimulation models provide a platform for policy makers and decision makers to understand the interaction between timber production activities (e.g. logging for lumber, pulp, biomass etc.) and the associated changes to terrestrial carbon stores in the above and below ground biomass.

1.2 Document Overview

This document provides a comprehensive overview of the timber and carbon geosimulation modelling platform. The document is structured as follows:

- 2.0 Overview: provides an overview of the model, introduces the model interface and outlines the primary research questions that drove model development.
- 3.0 Methods: summarizes the various steps that went into setting up and programing the model, along with descriptions of the various model algorithms that provide the main model functioning.
- 4.0 Results: highlights the preliminary results and demonstrates the models capabilities
- 5.0 Limitations: notes some of the current limitations
- 6.0 Future Directions: identifies potential future directions that could be explored to further advance the model.

[3] Intergovernmental Panel on Climate Change, Climate Change 2007: Synthesis Report. Working Group I Contribution to the Fourth Assessment Report of the IPCC (Cambridge University Press, 2007), 67.
[4] M. Obersteiner et al., The role of forests in carbon cycles, sequestration and storage, Issue 3: The economics of carbon sequestration in forests , IUFRO Newsletter No. 3, 2005, http://www.iufro.org/science/task-forces (accessed June 30, 2009).

2. Overview

The timber and carbon model is a spatially explicit simulation model that simulates forest growth, a carbon budget, and timber production (e.g. timber harvest, transport to mills, processing and sales) processes.

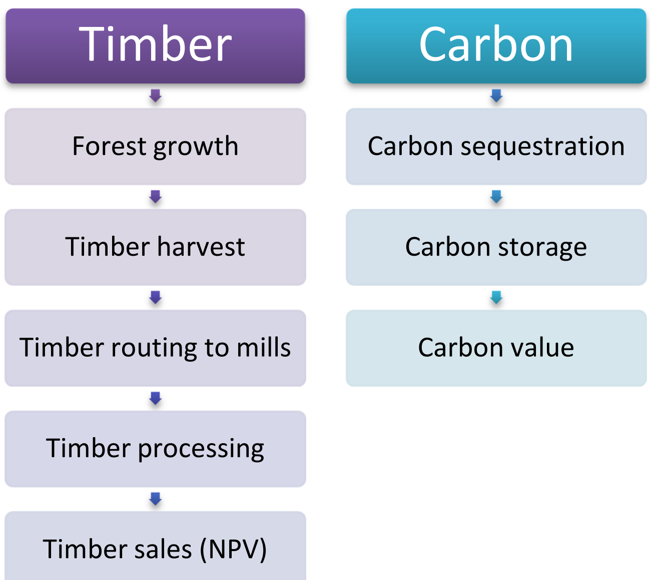

Figure 1: Model process figure

The model uses the Netlogo software (Wilenski, 1999) and is classified as a complex systems model. More specifically, it combines three model components, namely an agent-based model (ABM), cellular automata, and a network model. Figure 2 below depicts the timber and carbon model interface.

The timber and carbon model operates at an annual time step and has a variable spatial scale. The current application describing 7.4 million ha of the Upper Peace Land-use Framework (UPLUF) region has a 12 ha resolution. This area serves as a case study application. With a processed data library the model application can be extended all other land-use framework regions to capture the province of Alberta. The model imports GIS data and delineates the forest region of interest, represented by cells (as a gridded landscape) and agents (mills, raw harvested logs).

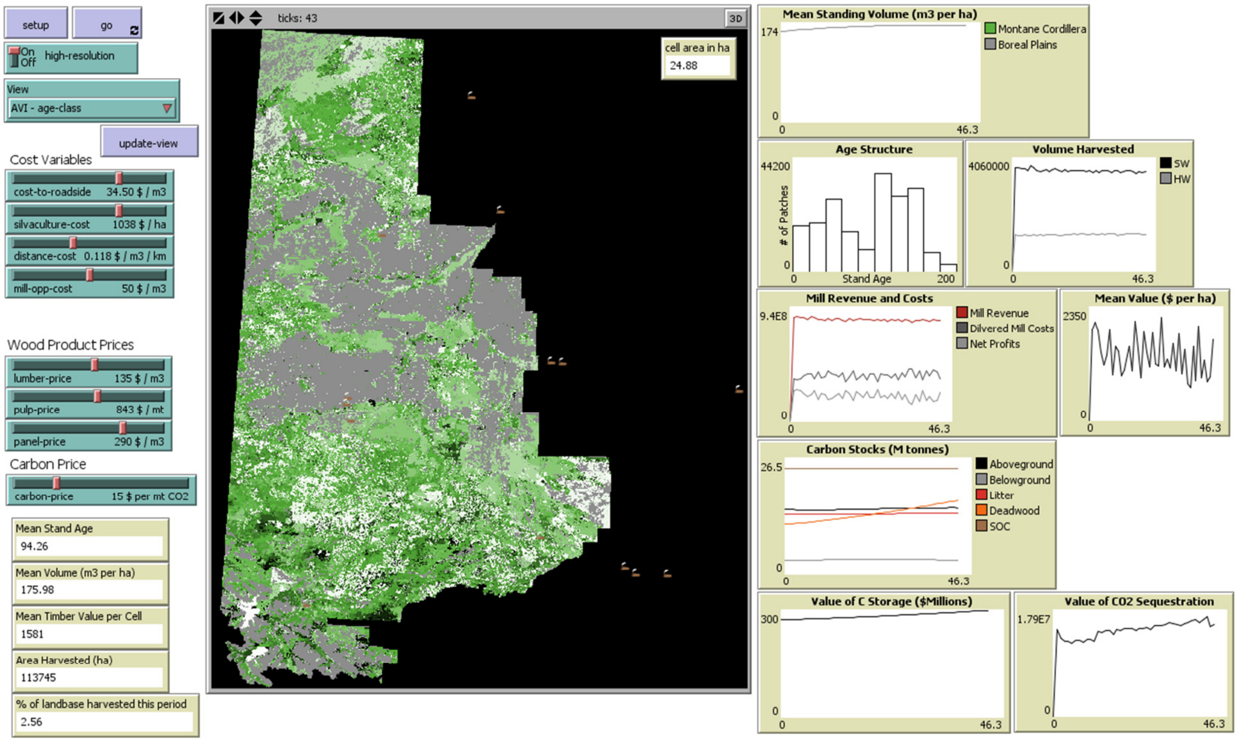

Figure 2: Model interface, depicting spatially-explicit landscape (forest stand and age data) with transportation networks, mills and climate stations. Different views present different GIS layers. Plots report model data, and can be exported to spreadsheets for analysis.

2.1 Research questions

The model provides timber and carbon flow estimations upon which other ABMs can operate and which can be used to answer two key research questions:

1. What is the spatial variation in the value of timber and carbon for forest stands in Alberta?
2. How do changes in forest economic interactions influence the provisioning of timber and carbon?

These research questions guide the level of detail required in model development.

3. Methods

Timber production and the carbon budget are modelled as two separate but integrated systems. Both systems are driven by the same spatial data and the total stock of carbon at any point in time is influenced by timber harvesting activities. This section outlines the methods and algorithms used to establish and integrate the two modelling systems.

In terms of timber production, the model relies on standardized forest yield equations, timber harvest protocols and the transportation of timber to mills for processing. All timber processes are maintained and modeled within the NetLogo framework. In terms of the carbon cycle, an external carbon budget model is utilized (see Section 2.5) to generate a series of detailed carbon equations that relate the stock of forest carbon to stand age (Appendix A).

The overall modelling process is depicted in Figure 3. Specific components of the model are described following the figure.

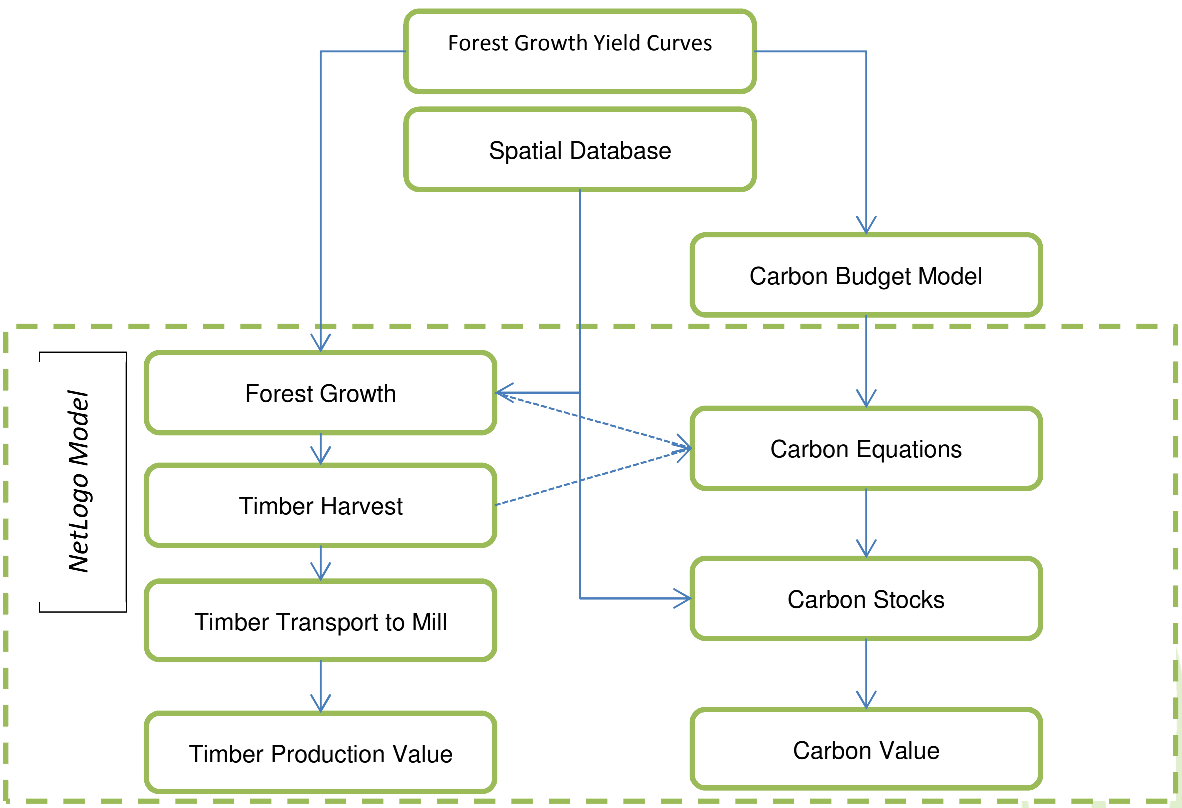

Figure 3: Overall Modelling Process

3.1 Variables and GIS Pre-processing Steps

As highlighted in Figure 3 above the model draws on range of spatial and other information sources as key data inputs outlined in Table 1.

Table 1: Data inputs into the NetLogo framework for the timber and carbon model

Data	Description	Data Source
Forest Management Agreement (FMA) boundaries	Polygon spatial data delineating FMA areas	Alberta Environment and Sustainable Resource Development (AESRD)
Forest Management Units (FMU) boundaries	Polygon spatial data delineating FMU	AESRD
Ecozone boundaries	Polygon spatial data delineating forest by ecozone	Environment Canada
Forest stands (or strata)	Extracted from enhanced vegetation layer data based on AVI and forest fire data	ABMI (2010)
Forest age class	Derived from enhanced vegetation layer data based on AVI and forest fire data	ABMI (Unpublished)
Eligible forest for harvest	Preprocessed spatial data outlining the landbase that is eligible and ineligible for harvest (e.g. protected areas and water course buffers are excluded from the eligible land base[5]	Processed by Silvacom and Green Analytics
Road network	Alberta 20k base road network	AltaLIS
Biomass producing / consuming facilities	Point locations of mills and biofuel facilities linked to fibre volume consumption	Silvacom and Green Analytics (2012)
Forest growth (yield curves)	Forest yields curves derived 5 forest strata	Natural Resources Canada (2006)
Carbon storage equations	Tonnes/ha of carbon stock estimates for forest strata by age class	CBM-CFS3 Carbon Model
Harvest cost to roadside	Per unit costs associated with harvesting and hauling logs to roadside	Peterson (2008)
Transportation costs	Per unit per km cost associated with hauling logs by different road types	Rouillard (2009)
Silviculture costs	Per ha silviculture costs for various silviculture treatments	Green et al. (2002)
Mill operational costs	Average cost of operating a mill per m^3 of production	Asante (2011)
Wood utilization	Regionally based wood product production statistics	Government of Alberta (2010).

[5] Ineligible and eligible areas are defined as per the Alberta Timber Harvest Planning and Operating Ground Rules Framework. Available online: http://esrd.alberta.ca/lands-forests/forest-management/documents/TimberHarvest-OperatingGroundRules-Jun2012.pdf

Wood product prices	Market composite wood product prices for a range of processed products (lumber, pulp, panel boards, etc.)	Random Lengths (2013); CME Group (2013)

The foundation of the model is the geospatial database which contains a number of the data items identified in Table 1. The following provides the steps taken to process the information for modelling. Metadata is provided for each item in Appendix B.

1. ABMI Strata/Age Class pulled from ABMI's enhanced vegetation data
    a. Defined forest ageclass and strata (as described in section 3.3)
    b. Selected ABMI tiles pertinent to area of interest (in this case the LUF boundary)
    c. Dissolved on ABMI_STRAT or AGECLASS fields
    d. Projected data to common coordinate system
    e. A rasterized version was created at a 500m resolution and converted to ascii format for input into the model this created two separate ascii files (1) delineating forest strata; and (2) delineating forest age class.
2. Forest Management Areas (FMA)
    a. Clipped data to area of interest (in this case the LUF boundary)
    b. Projected data to common coordinate system
3. Forest Management Units (FMU)
    a. Clipped data to area of interest (in this case the LUF boundary)
    b. Projected data to common coordinate system
4. Ecozones
    a. Downloaded data set from Agriculture Canada
    b. Clipped data to area of interest (in this case the LUF boundary)
    c. Projected data to common coordinate system
5. Mills
    a. Drawing on disposition data tied to forest management plans for each FMU within the LUF boundary a spatial point data layer was created
    b. Projected data to common coordinate system
6. Parks/Protected Areas
    a. Clipped data to area of interest (in this case the LUF boundary)
    b. Projected data to common coordinate system
7. Green/White Zones

   a. Clipped data to area of interest (in this case the LUF boundary)
   b. Projected data to common coordinate system
8. Indian Reserves
   a. Clipped data to area of interest
   b. Projected data to common coordinate system
9. Water Buffers
   a. Clipped data to area of interest (in this case the LUF boundary)
   b. Extracted applicable road classes
   c. Buffered streams at pre-determined widths based on stream class
      - Permanent lakes greater than 4 hectares were buffered 100m.
      - Polygonal rivers were buffered 60m.
      - Single line streams were buffered 30m either side.
   d. Projected data to common coordinate system
10. Ineligible land base
   a. Created a union layer of protected areas, reserves, and water buffers
   b. Rasterized the unionized layer at a 500m resolution to create a file represent land patches considered ineligible for harvest

3.2 Model Agents, Patches, and Variables

The model contains a number of components (e.g. agents and patches) and a large range of variables in order to simulate forest growth, harvest, and ultimately timber and carbon values. Tables 2 and 3 summarize all model components and variables.

Table 2: Model components (agents and patches)

Component Name	Type	Description
land-patches	Patch agent set	A subset of the NetLogo "world" patches that represent only those patches within the LUF area
forest-patches	Patch agent set	A subset of land-patches that represent only those patches defined as forest by AMBI vegetation data layer
eligible-forest	Patch agent set	A subset of forest-patches that represent only those patches eligible for harvest
harvested-patches	Patch agent set	A subset of eligible-forest patches that represent only those patches that have been harvested in the current time period
mills	Agent	Agents that represent lumber, pulp, or OSB producers drawing wood from the FMU's within the LUF area.

Table 3: Model variables

Variable	Variable Type	Description	Units
ecozone-dataset	Global	GIS data input of ecozones	Nominal
age-dataset	Global	GIS data input of forest age	Age of forest stands in 10 year categories
strata-dataset	Global	GIS data input of forest strata	Nominal
eligible-dataset	Global	GIS data input of protected or otherwise ineligible areas for harvest	Nominal
mills-dataset	Global	GIS data input of mills	NA
fmu-dataset	Global	GIS data input of FMU	Nominal
area	Global	Sets the area per patch for the models current resolution	Hectares
value-per-ha	Global	Calculates and tracks average value per ha of harvested patches	$CAD per ha
npv	Global	Calculates and tracks the net present value timber harvest from all harvested patches	$CAD
npv-vol	Global	Calculates and tracks the total volume harvested associated with npv	m^3
npv-per-m^3	Global	Calculates and tracks the average net present value per m^3 (npv/npv-vol)	$CAD per m^3
Cost-to-roadside	Global	Assumed harvest costs to roadside, set by model user (default setting is $35)	$CAD per m^3
Silvaculture-cost	Global	Assumed silvaculture costs associated with harvested patches, set by model user (default setting is $1000)	$CAD per ha
Distance-cost	Global	Assumed unit costs for transporting wood to mills, set by model user (defult setting is $0.120)	$CAD per m^3 per km
Mill-opp-cost	Global	Assumed mill operational costs to process wood into wood products, set by model user (default setting is $50)	$CAD per m^3
Lumber-price	Global	Current lumber price, set by model user (default setting is $135)	$CAD per m^3
Pulp-price	Global	Current pulp price, set by model user (default setting is $843)	$CAD per metric ton
Panel-price	Global	Current panel price, set by model user (default setting is $290)	$CAD per m^3
Carbon-price	Global	Current carbon price, set by model user (default setting is $15)	$ per metric ton CO_2
is-land-patch	Patch	Variable taking the value of 1 or 0 used to set land-patches agent set	Dichotomous
is-forest-patch	Patch	Variable taking the value of 1 or 0 used to set forest-patches agent set	Dichotomous
is-eligible	Patch	Variable taking the value of 1 or 0 used to	Dichotomous

		set eligible-forest agent set	
ecozone	Patch	ecozone-dataset allocated to patches	as above
fmu	Patch	fmu-dataset allocated to patches	as above
elibible	Patch	eligible-dataset allocated to patches	as above
age-class	Patch	age-dataset allocated to patches	as above
strata	Patch	strata-dataset allocated to patches	as above
stand-age	Patch	Represents stand age allocated to patches based on age-class	Age in years
total-patch-volume	Patch	Total volume for each patch as calculated based on yield curves	m^3
conifer-volume	Patch	Conifer volume for each patch as calculated based on yield curves	m^3
deciduous-volume	Patch	Decid volume for each patch as calculated based on yield curves	m^3
my-patch-vol-harvested	Patch	Calculates, sets, and stores the volume harvested from each patch	m^3
timber-esv	Patch	Calculates timber production value for each patch by multiplying npv-per-m^3 by my-patch-vol-harvested	$CAD per patch
timber-evsp	Patch	Calculates potential timber production (i.e. unharvested eligible forest volume) value for each patch by multiplying npv-per-m^3 by total-patch-volume	$CAD per patch
aboveground-soft	Patch	Calculates above ground forest carbon from conifer (see appendix A)	Tonnes of Carbon
aboveground-hard	Patch	Calculates above ground forest carbon from decid (see appendix A)	Tonnes of Carbon
belowground-soft	Patch	Calculates below ground forest carbon from conifer (see appendix A)	Tonnes of Carbon
belowground-hard	Patch	Calculates below ground forest carbon from decid (see appendix A)	Tonnes of Carbon
dom-above-other	Patch	Calculates above ground carbon content of dead organic matter other than forest litter (see appendix A)	Tonnes of Carbon
dom-above-litter	Patch	Calculates above ground carbon content of dead organic matter from forest liter (see appendix A)	Tonnes of Carbon
dom-below-slow	Patch	Calculates below ground carbon content of slow decomposing dead organic matter (see appendix A)	Tonnes of Carbon
dom-below-fast	Patch	Calculates below ground carbon content of fast decomposing dead organic matter (see appendix A)	Tonnes of Carbon
dom-below-vfast	Patch	Calculates below ground carbon content of very fast decomposing dead organic matter	Tonnes of Carbon

		(see appendix A)	
ipcc-above	Patch	Regroups the carbon categories to match ipcc categores	Tonnes of Carbon
ipcc-below	Patch	Regroups the carbon categories to match ipcc categores	Tonnes of Carbon
ipcc-litter	Patch	Regroups the carbon categories to match ipcc categores	Tonnes of Carbon
ipcc-deadwood	Patch	Regroups the carbon categories to match ipcc categores	Tonnes of Carbon
ipcc-soc	Patch	Regroups the carbon categories to match ipcc categores	Tonnes of Carbon
ipcc-total	Patch	Sum of all ipcc carbon groupings	Tonnes of Carbon
carbon-esv	Patch	Stock of forest carbon in CO_2e for each patch multiplied by the carbon price (in $ per CO_2)	$CAD per patch
ccs	Patch	Represents the carbon flux on each patch by calculating the carbon capture and storage for each period t	$CAD
sw-vol-harvested	Agent	Conifer volume harvested in period t	m^3
hw-vol-harvested	Agent	Decid volume harvested in period t	m^3
mill-id	Agent	GIS data applied to mills attributing each mill an id number	Nominal
mill-name	Agent	GIS data applied to mills attributing each mill its operating name	Categorical
mill-type	Agent	GIS data applied to mills attributing each mill an operational type (Sawmill, Pulp mill, OSB mill, or some combination)	Categorical
my-mill-patches	Agent	A variable that defines where each mill can and cannot harvest in each period (defined as stand > 80 years and within the mills corresponding FMU)	A set of patches
my-aac-sw	Agent	GIS data applied to mill attributing each mill its coniferous annual allowable cut	m^3 per year
my-aac-hw	Agent	GIS data applied to mill attributing each mill its deciduous annual allowable cut	m^3 per year
patches-harvested	Agent	A variable that allows each mill to track which patches it has during the current period	A set of patches
area-harvested	Agent	A variable that allows each mill to track how much area it has harvested during the current period	hectares
gross-merch-vol-sw	Agent	Adjust the total sw-vol-harvested to account for only merchantable volume (assumed to be 92% of total volume)	m^3
gross-merch-vol-hw	Agent	Adjust the total hw-vol-harvested to account for only merchantable volume (assumed to be 92% of total volume)	m^3

cumulative-vol	Agent	A variable that allows each mill to track the total volume harvested across all time periods	m^3
avg-dist-to-mill	Agent	Determines the average distance to the mill by summing the distance from each harvested patch to its corresponding mill and dividing by the number of patches harvested	km
haul-cost	Agent	Calculates the total haul cost for each mill by multiplying the distance-cost ($ per m^3 per km) by avg-dist-to-mill by and harvested volume in period t	$CAD
delivered-mill-cost	Agent	Calculates the delivered mill cost in the current period (see section 3.6)	$CAD
mill-cost	Agent	Calculates all mill costs in the current period (see section 3.6)	$CAD
mill-revenue	Agent	Calculates the mill revenue from sale of forest products (see section 3.6)	$CAD
net-profit	Agent	Calculates net profit (mill-revenue minus mill-cost) for each mill in the current period	$CAD

3.3 Forest growth

The forest growth algorithm is driven by the yield curve relationship between stand volume and stand age. Standardized yield relationships were developed for this model based on data from the Canada National Forest Inventory (Natural Resources Canada, 2006) to represent the two primary forest ecozones in Alberta: the boreal plain and the montane cordillera.[6]

The developed yield curves vary by stand type or "strata." For each ecoregion, five stand strata were defined based on forested ABMI land classes and percent pine content from the ABMI enhanced vegetation layer (Table 4).

Table 4: Allocation of ABMI land cover class to forest strata

ABMI Land Cover Class	Percent Pine (Enhanced Vegetation Layer)	Assigned Strata
210 – Coniferous Forest	< 50%	C-S
210 – Coniferous Forest	≥ 50%	C-P
230 – Mixed Forest	< 50%	MX-S
230 – Mixed Forest	≥ 50%	MX-P
220 – Broadleaf Forest	N/A	D

[6] Two other ecozones also exist within Alberta (Prairies and Taiga Plain). The prairies ecozone is dominantly agricultural with little timber production. While some forest production falls within the taiga plains, it was assumed that this area followed a similar growth patterns to the boreal plains.

A total of 10 yield curves are programed into the model, five for the boreal plain and five for the montane cordillera, the yield curves are summarized in Table 5. Using the assumed species distribution (also summarized in Table 5), each forest growth volume for each strata is separated into volume conifer and volume deciduous.

Table 5: Yield curve equations by ecozone and strata

			Species Distribution[b]	
Ecozone	**Strata**	**Total Volume Equation[a]**	**Percent Conifer**	**Percent Deciduous**
Boreal Plain	**C-S**	y = -0.0063x^2 + 2.2359x - 7.833	87.5%	12.55%
Boreal Plain	**C-P**	y = -0.0121x^2 + 3.6973x - 23.793	87%	12.5%
Boreal Plain	**MX-S**	y = -0.021x^2 + 5.0445x - 15.955	50%	50%
Boreal Plain	**MX-P**	y = -0.0181x^2 + 4.6205x - 35.769	50%	50%
Boreal Plain	**D**	y = -0.0139x^2 + 3.5775x + 5.0728	12.5%	87.5%
Montane Cordillera	**C-S**	y = -0.0049x2 + 3.1472x - 20.612	87.5%	12.5%
Montane Cordillera	**C-P**	y = -0.0081x2 + 3.5594x - 22.409	87.5%	12.5%
Montane Cordillera	**MX-S**	y = -0.0096x2 + 4.111x - 42.67	50%	50%
Montane Cordillera	**MX-P**	y = -0.0073x2 + 3.5106x - 25.912	50%	50%
Montane Cordillera	**D**	y = -0.012x2 + 3.4575x - 24.277	12.5%	87.5%

Table notes: *(a) Derived CANFI reports of total volume and strata area (Natural Resources Canada 2006). Note: y represents yield in m^3 / ha and x represents stand age in years.*
(b) Assumed species distribution percentages as mid-point conifer percent cover values used in ABMI landcover assignments (ABMI, 2010).

Each yield curve determines total tree volume v_{jsa} in m^3/ha of timber type *j* obtained from forest strata *s* of age *a* during period *t*. Total timber volume of type *j* harvested from cells *c* is calculated as follows:

$$V_{jst} = \sum_{j} v_{jsa} x_{cjat} \quad c \in A_t$$

Where x is the area harvested and A_t is the set of all cells harvested during time *t.*

Forest Growth Algorithm:

The model pulls in key spatial reference data (i.e. FMA boundaries, FMU boundaries, ecozone boundaries, stand age, forest strata type) and allocates each cell within the model with the appropriate information. The algorithm then calls each forest cell within the model and calculates standing volume by applying the yield equation that matches each cell's references information (i.e. Boreal Plain ecozone, C-S Strata) and associated stand age. The algorithm also ages each cell by adding one year to its age variable as the model progresses through time.

3.4 Timber harvest

Similar to Hauer et al. (2010), the model captures demand for timber spatially, based on the location of mills in the study area. In doing so, the model accounts for the spatial and temporal patterns associated with timber production costs and revenue. Each mill, M, is assigned sources of timber volume levels (i.e. FMA and FMU based on historical trends), a production capacity level (based on this historical public record), a mill type (i.e. sawmill, pulp and paper, etc.), and a preferred timber type (i.e. conifer or deciduous).

The harvest algorithm asks each mill to examine its allocated forest area and harvests the oldest forest stands eligible for harvest.[7] Each forest cell is defined as either eligible or ineligible based on pre-processed spatial GIS data that allocates eligibility based on standard criteria for Alberta (for example protected areas and riparian zones are ineligible for harvest).

The annual allowable cut (AAC) for the LUF is allocated to the mills associated with the FMU's within the LUF boundary (adjusted by the percent of each FMU within a given LUF boundary). Mills continue to harvests from the oldest eligible remaining cells until the reach a percentage of their allocated annual allowable cut. The percentage of AAC is used to account for the fact that actual wood harvest tends to be less than total AAC. This reduction is based on reported harvest statistics for LUF regions (AESRD, 2013).

The volume harvested from each cell is adjusted to account for only the merchantable volume and standard cull factors, which account for rot and breakage during harvest. Merchantable volume adjustments are based on CBM-CFS3 rates and assumed to be 92.5% of total tree volume for conifer and 91% for deciduous. Standard Alberta cull factors are used, 2% for conifer and 5% for deciduous.

Once harvested the stand age of each harvested cell is set to zero and the adjusted harvested volume is sent to the mill. Harvested wood is routed to the source mill based on shortest distance.

[7] There are a lot of operational factors that go into final harvesting plans including distance, piece size, seasonal ground etc. Each company is different in their approach. They are often trying to balance these things over the long term so that they are not simply liquidating the "cheap" wood now, although this does happen in some cases. Oldest first is a standard practice for strategic level simulation modeling. Optimization modeling typically does not follow oldest first.

3.5 Calculation of timber production net present value

The value of timber production is defined as the market value generated from a given volume of timber. Therefore, to calculate and map timber production values, wood product processing also had to be modelled. In essence, the value of timber production is equal to the profits generated at the mill from selling processed timber. The model tracks the flow of wood volume and calculated mill profits are mapped back to the land based on the amount of wood that flowed from each cell in any given time period.

Net profits *NP* of Mill *m* is defined as follows:

$$NP_m = \sum R_{mpt}\left(Q_{jmt}\right) - \sum DMC_{mt} - OC_m$$

Where R_{mpt} is revenue for mill *m*, from wood products *p*, in period *t*, which is a function of the delivered mill volume Q_{jmt} , DMC_{mt} is the delivered mill cost for mill *m* in period *t*, and OC_m is the operational cost of processing wood products at mill *m*.

Revenue is determined for each mill based on the volume of wood processed and the mill type, which determines the wood products produced at each mill. Revenue is expressed as follows:

$$R_{mpt} = \sum_{p} P_p \times Q_{jmt} \times U_{pj}$$

Where P_p is the price for wood product *p* (where *p* is lumber, pulp and paper, oriented strand board, or Vaneer) and U_{pj} is a mill utilization factor for wood product *p* from timber type *j*. Wood product prices are determined based on current market prices for each wood product type.

The cost of delivering wood to each mill is the sum of roadside harvest costs RS_{jt} in \$/m^3 of timber type *j* during period *t*, silviculture costs $Silv_{st}$ in \$/ha for strata s in period t, and the haul cost HC_{mt} to mill *m*, in period *t*.

$$DMC_{mt} = \sum RS_{jt} \times Q_{jt} + \sum Silv_{st} \times x_{st} + \sum HC_{mt}$$

Haul costs are determined through the wood flow routing process that determines the haul distance between the forest cell harvested and the target mill based on road type (e.g. highway, primary roads, secondary roads, etc.). Therefore,

$$HC_{mt} = \sum Dis_{rm} \times Fric_r \times Q_{jmt}$$

where Dis_{rm} is the distance in km traveled on road type *r* between the harvest location and the destination mill *m*. $Fric_r$ is the friction cost in \$/km/m^3 associated with road type *r*.

3.6 Carbon budget model

As is demonstrated in Figure 3 above, accounting for carbon is done through coupling the carbon budget model (CBM-CFS3) and the NetLogo framework. Through the carbon model process the CBM-CFS3 model is run to generate key relationships between pools of carbon and forest stand type and age. Note that a number of carbon models were considered for this analysis and the CBM-CFS3 model was chosen based on its ability to interact with the forest growth and timber harvesting processes.

A number of steps are required to establish the necessary relationships between the carbon and timber production models. The approach followed to convert forest stand yields to forest carbon curves is similar to that adopted by Price et al. (1997). To assign forest carbon values to forest stands in the timber production model, forest carbon estimation parameters were used from the CBM-CFS3. The CBM CFS3 is a forest ecosystems dynamics simulation model developed by the CFS for use by forest managers and analysts to estimate and track forest carbon as it shifts among the forest carbon pools (Kurz et al, 2009).

The CBM-CFS3 was used to convert stand projections of hardwood and softwood species merchantable volume (m^3/ha) into carbon (C) stored in living biomass (stem wood, foliage, stumps, branches, bark, coarse and fine roots) and dead organic matter pools (leaf litter, forest floor and soil detritus, standing snags and branches, coarse woody debris, and soil organic matter).

The process adopted was as follows. First, forest strata yield curves are entered in to the CBM-CFS3 model for each ecozone. Second, a stand level simulation is run for each strata and ecozone combination. The CBM-CFS3 model uses deterministic equations to calculate carbon. After a 200 year simulation, the model outputs a series of carbon stock data (in tonnes per ha) for each strata within each ecozone. From this output data a series of “carbon storage” equations are developed by regressing carbon stocks against stand age. Figure 4 provides an example of a 2 such regression equations, based on the CBM-CFS3 model output. All fitted curves had an R^2 greater than 0.92, with the exception of DOM below ground very fast which had an R^2 ranging from 0.1 to 0.6. While this suggests a poor fit to the data, this carbon pool accounts for a tiny fraction of the total carbon (less than 1%). Consequently, we do not anticipate this to significantly affect the model’s functioning.

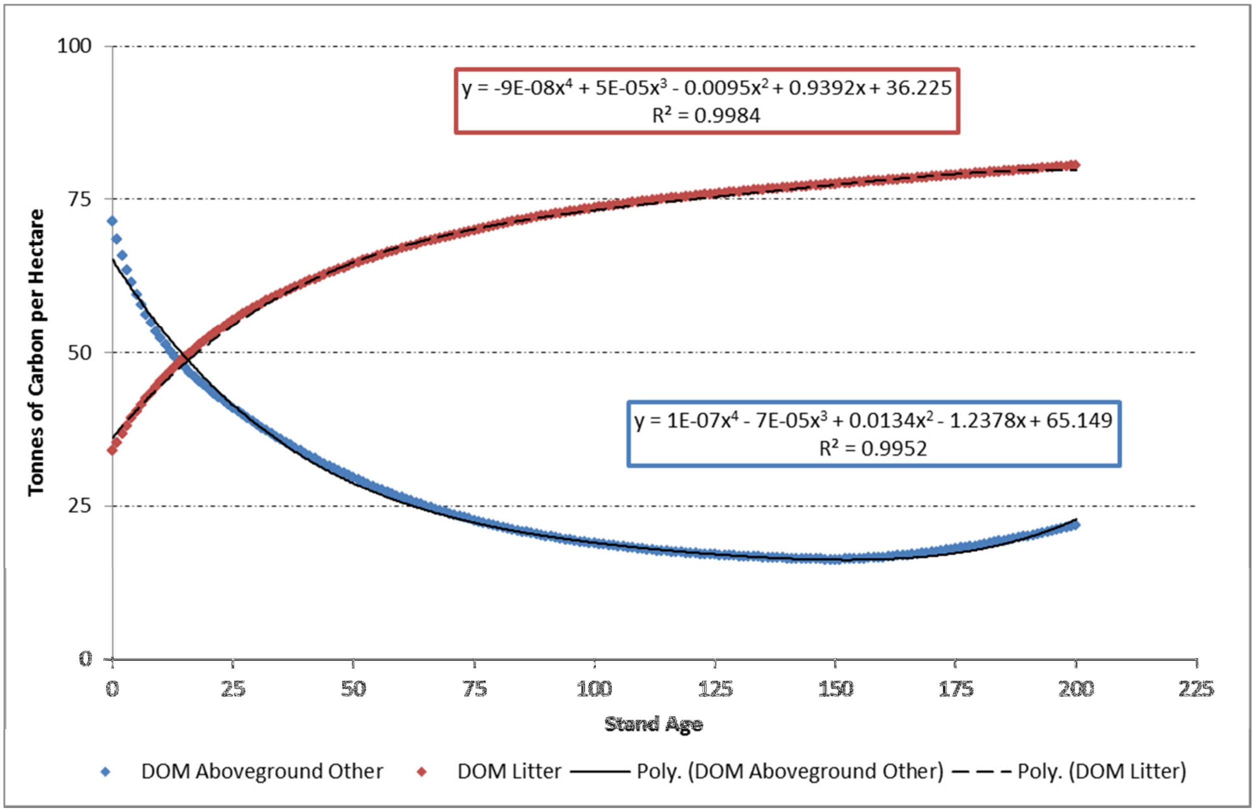

Figure 4: CBM-CFS3 model data outputs, fitted curves, and regression equations for DOM Aboveground and DOM Litter carbon pools provided by deciduous stands in the Montane Cordillera ecozone.

These relationships are then coded in NetLogo to interact with the dynamic forest growth and harvest processes. It should be noted that accounting for carbon decay of forest products was out of scope for this stage of the model development. Future iterations of the timber and carbon model should account for forest product life cycle connection to carbon storage and sequestration. The current model assumes forest products hold their carbon content indefinitely.

Figure 5 depicts the carbon pools that can be tracked within the CBM-CFS3 model and how they are aggregated for the purposes of the carbon yield equations inputted into NetLogo. Nine different carbon pools are tracked within the timber and carbon model, and each pool is differentiated by five forest strata and the two relevant ecozones, resulting in a total of 90 carbon yield equations (reported in Appendix A). These are then further aggregated within NetLogo to match IPCC standard carbon categories following Kurz et al. (2009).

It should also be noted that carbon pools referred to as organic matter or biomass are converted to carbon content within CBM-CFS3. This was done using the default biomass to carbon conversion of 50% (or factor 2) similar to Kurz et al. (2009). Therefore, despite the terminology used for carbon pools, the CBM-CFS3 model outputs report carbon content in tonnes of carbon.

CBM-CFS3 Carbon Pools					Pools Reported	IPCC GPG Pools
Total Ecosystem					Total Ecosystem	
Total Ecosystem	Biomass				Biomass	
Total Ecosystem	Biomass	Aboveground Biomass			Aboveground	Aboveground Biomass
Total Ecosystem	Biomass	Aboveground Biomass		Softwood Merchantable Softwood SubMerchantable Softwood Other Softwood Foliage	Softwood	Aboveground Biomass
Total Ecosystem	Biomass	Aboveground Biomass		Hardwood Merchantable Hardwood SubMerchantable Hardwood Other Hardwood Foliage	Hardwood	Aboveground Biomass
Total Ecosystem	Biomass	Belowground Biomass			Belowground	Belowground Biomass
Total Ecosystem	Biomass	Belowground Biomass		Softwood Fine Roots Softwood Coarse Roots	Softwood	Belowground Biomass
Total Ecosystem	Biomass	Belowground Biomass		Hardwood Fine Roots Hardwood Coarse Roots	Hardwood	Belowground Biomass
Total Ecosystem	Dead Organic Matter				Dead Organic Matter	
Total Ecosystem	Dead Organic Matter	Aboveground DOM			Aboveground	
Total Ecosystem	Dead Organic Matter	Aboveground DOM	Litter	Aboveground Very Fast DOM Aboveground Slow DOM Aboveground Fast DOM	Litter	Litter
Total Ecosystem	Dead Organic Matter	Aboveground DOM		Medium DOM Softwood Stem Snag Softwood Branch Snag Hardwood Stem Snag Hardwood Branch Snag	Other	Deadwood
Total Ecosystem	Dead Organic Matter	Belowground DOM			Belowground	
Total Ecosystem	Dead Organic Matter	Belowground DOM	Soil C	Belowground Very Fast DOM	Belowground Very Fast DOM	Soil Organic Carbon
Total Ecosystem	Dead Organic Matter	Belowground DOM	Soil C	Belowground Slow DOM	Belowground Slow DOM	Soil Organic Carbon
Total Ecosystem	Dead Organic Matter	Belowground DOM		Belowground Fast DOM	Belowground Fast DOM	Deadwood

Figure 5: CBM-CFS3 carbon pools built into the model

3.7 Carbon storage and sequestration value

The value of carbon storage and sequestration is determined by applying a carbon market price to the tonnes of carbon storage and sequestration (or rate of change in the stock of carbon). Current prices for carbon vary widely depending on the market and the extent to which social costs of carbon emissions are included. Given this variably, the model is programed with an adjustable carbon price ranging from $0 to $150 per tonne of carbon.

In the province of Alberta, the Emission Reduction Regulations for large industrial emitters set a carbon price of $15 per tonne of CO_2e, which converts to $55.05 per tonne of carbon. British Columbia carbon tax is $25 per tonne of CO_2e or $91.75 per tonne carbon.

The U.S. federal government develop an estimate to be used in cost-benefit analyses of potential U.S. federal regulations, which ranges from \$5 to \$65 per ton of CO_2e (2007 U.S. \$). In 2012 CAD per metric tonne of carbon, the average price equates to \$75.78. Finally, Environment Canada used \$94.64 per tonne of carbon in its Regulatory Impact Analysis Statement on the Renewable Fuels Regulations.

The carbon prices captured in the carbon model allow for a range of carbon prices to be applied to changes in carbon stocks to reflect different climate policy scenarios.

The model applies carbon values in two ways (1) value of stock of stored carbon in the forest; and (2) value of carbon flux (i.e. sequestered carbon during each period). Stock values are calculated for each patch by adjusting the carbon stock to CO_2e and multiplying by the model user specified carbon price. This produces a map of carbon stock values across the LUF. Carbon sequestration values are mapped in a similar way. However, it is calculated by subtracting the period ending carbon by the period opening carbon to estimate the carbon flux. It should be noted that ending carbon is calculated before harvest, implicitly assuming that carbon content of harvested volume is maintained in its ultimate wood product. Future work could explore relaxing this assumption to account for carbon life cycle of products.

4. Results

The model is capable of producing a range of outputs and conducting various scenario and sensitivity analyses, such as exploring how changing wood product prices or haul costs impact timber production values and carbon storage. However, the primary objective of model at this stage is the development of timber production and carbon value maps. Below we present draft maps produced by the model for a test region. The maps display timber production and carbon values for status quo conditions. The figures provide examples of the models current mapping outputs. The model can output these as raster based maps which can be imported into GIS, stitched together with other LUF regions or overlaid with existing spatial data for future analysis or mapping.

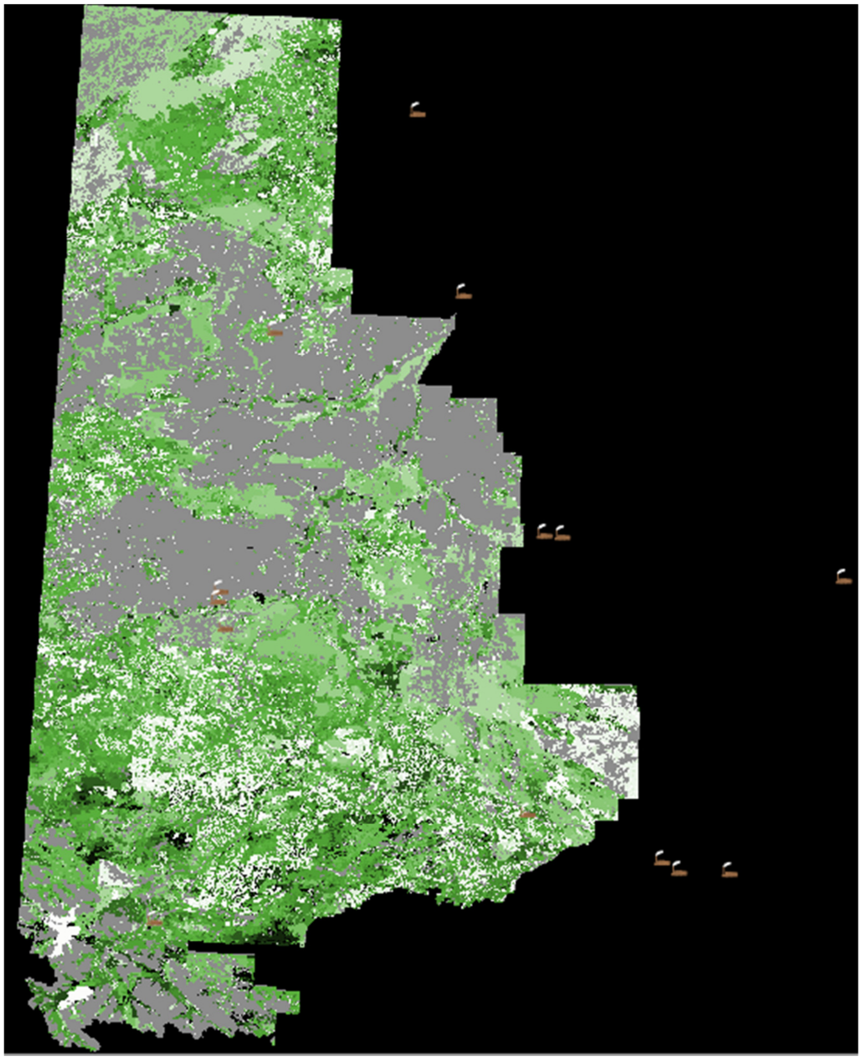

Figure 5: Distribution of forest stand age after 50 timber production simulation. Grey areas represent non-forest areas, stand age is represented by green (darker green being oldest, lighter green being youngest).

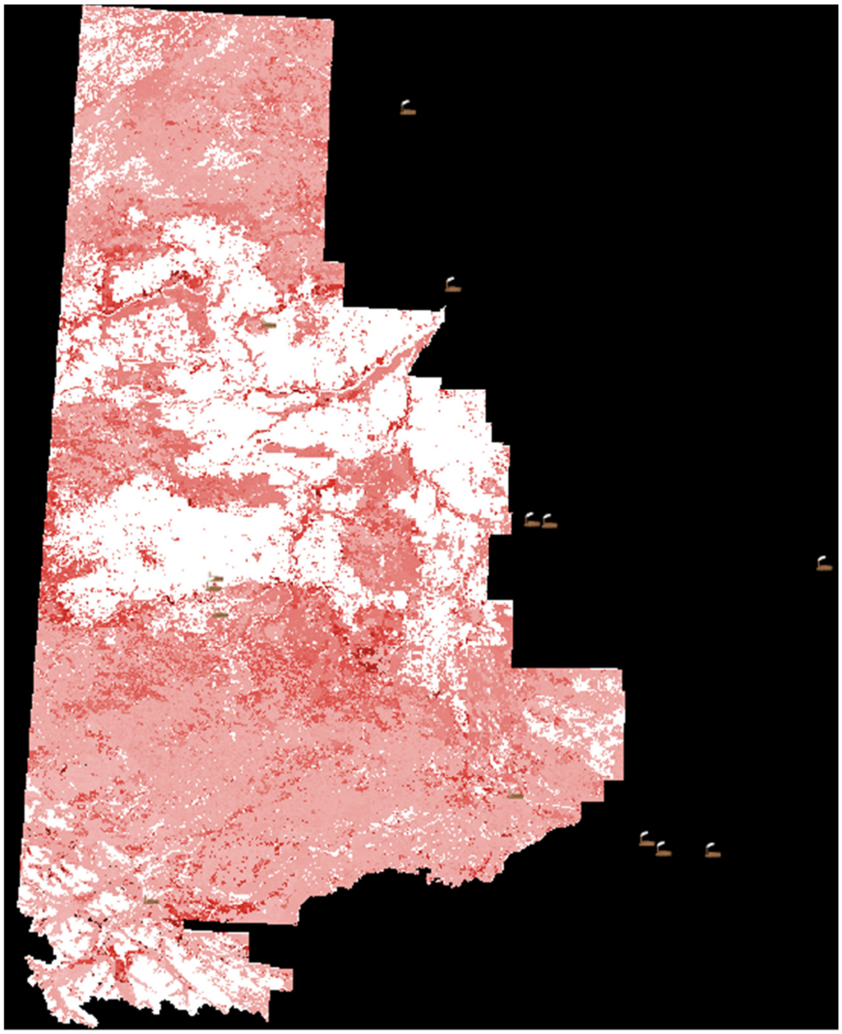

Figure 6: Map of carbon value (darker red having the highest value and lighter red having lower NPV, white areas are non-forested areas).

Figure 6: Map of net present value of timber production value, over 50 years (darker red having the highest value and lighter red having lower NPV).

5. Limitations

The current version of the model is limited by a few factors including:

- The size of the landscape (and related resolution) that can be modelled is limited. The model requires balancing a fine enough resolution to approximate the amount of eligible forest for harvest (i.e. extracting linear disturbance such as pipelines) while keeping the scale coarse enough to capture the flow of harvested timber to mills for processing.
- Haul transportation costs are currently calculated using a straight line distance between the harvested location and target mill. As a result transportation costs may be slightly under estimates. However, at an aggregate level model outputs appear in line with aggregate statistics reported on LUF boundaries.[8] A transportation routing algorithm was explored and a preliminary version is in development, however, this requires complex routing routines and has been left out of this version.
- The environment in which the modelling takes places assumes fixed climate conditions. In the future as GHG emissions concentrate in the atmosphere variations in temperature and moisture, and CO_2 emissions themselves will influence the productivity of boreal forest sites. Currently, the timber and carbon model do not capture future climate changes.
- The model currently is only focused on the existing “managed forest” and does not consider future land removal by oil and gas footprint, nor afforestation from oil & gas reclamation.

[8] Statistics Canada reports that forest products accounts for about $4 billion of GDP annually (Alberta Government 2012) and Upper Peace LUF, for example, accounts for about 25% of activity (AESRD 2012), which would be about $1 billion of GDP. The Upper Peace model generates revenues of just under $1 billon dollars.

6. Future Directions

While the current timber and carbon models capture the best publicly available science and data for Alberta, there are a number of areas for further research that could improve the current model development. Below are key areas for future research and development organized by model type.

Timber Production Model

- Validating a number of key assumptions in the timber model related to how raw logs are traded between forest product companies. In the current model some basic assumptions are made related to least cost timber trading occurs. In reality, a suite of endogenous industry norms, constraints and relationships governs the trading of raw logs. Future research would seek to validate key log trading rules to better capture the spatial distribution of raw logs across the forest landscape.
- The Net Logo modelling software allows model development to include agent-based interactions. As such, the model could be expanded to better capture the endogenous economic dynamics that govern the Alberta forest industry. Price sensitivity, cost sensitivity, availability of logging truck companies and season constraints in log hauling are a few of many variables that can be captured in the Net Logo model.

Carbon Model

- The data exists to capture the expected climate variation that will occur in northern Alberta as a result of climate change. Future research and model development should include the expected changes to biomass productivity as a result of increases in GHG emissions in the atmosphere.
- The carbon budget estimations currently include the gains and losses to a carbon budget as a result of a discrete set of land use changes, including timber harvesting and forest growth. However, the current model does not capture gains or losses of GHG emissions as a result of fossil fuel use in the forest industry. Future model development would include this data to better capture how the provisioning of timber related ecosystem services affect the production of GHG emissions.

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Appendix A. Carbon Pool Equations

Table 6: Carbon equations from the CBM-CFS3 model (y = tonnes of carbon and x = stand age). Note equation parameters are rounded for reporting simplicity, actual coded equations within the model contain more precise equations.

ecozone	Strata	Carbon Pool	Equation
Boreal Plains	C-S	Aboveground Softwood	$y = -6E\text{-}11x^6 + 4E\text{-}08x^5 - 1E\text{-}05x^4 + 0.0013x^3 - 0.0855x^2 + 3.1056x$
Boreal Plains	C-S	Aboveground Hardwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 3E\text{-}06x^4 + 0.0004x^3 - 0.0258x^2 + 0.7338x$
Boreal Plains	C-S	Belowground Softwood	$y = -1E\text{-}11x^6 + 9E\text{-}09x^5 - 2E\text{-}06x^4 + 0.0003x^3 - 0.019x^2 + 0.6894x$
Boreal Plains	C-S	Belowground Hardwood	$y = -1E\text{-}11x^6 + 8E\text{-}09x^5 - 2E\text{-}06x^4 + 0.0003x^3 - 0.0158x^2 + 0.4394x$
Boreal Plains	C-S	DOM Aboveground Other	$y = 1E\text{-}07x^4 - 8E\text{-}05x^3 + 0.0144x^2 - 1.2761x + 62.51$
Boreal Plains	C-S	DOM Aboveground Litter	$y = -5E\text{-}08x^4 + 2E\text{-}05x^3 - 0.0046x^2 + 0.4329x + 52.912$
Boreal Plains	C-S	DOM Belowground Slow	$y = 0.0002x^2 - 0.0245x + 116.16$
Boreal Plains	C-S	DOM Belowground Fast	$y = 7E\text{-}08x^4 - 3E\text{-}05x^3 + 0.0051x^2 - 0.328x + 8.5561$
Boreal Plains	C-S	DOM Belowground Very Fast	$y = -4E\text{-}06x^2 + 0.0018x + 1.7513$
Boreal Plains	C-P	Aboveground Softwood	$y = -4E\text{-}11x^6 + 3E\text{-}08x^5 - 8E\text{-}06x^4 + 0.001x^3 - 0.0655x^2 + 2.5319x$
Boreal Plains	C-P	Aboveground Hardwood	$y = -3E\text{-}11x^6 + 2E\text{-}08x^5 - 5E\text{-}06x^4 + 0.0007x^3 - 0.0432x^2 + 1.3132x$
Boreal Plains	C-P	Belowground Softwood	$y = -1E\text{-}11x^6 + 7E\text{-}09x^5 - 2E\text{-}06x^4 + 0.0002x^3 - 0.0145x^2 + 0.5621x$
Boreal Plains	C-P	Belowground Hardwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 3E\text{-}06x^4 + 0.0003x^3 - 0.0218x^2 + 0.6283x$
Boreal Plains	C-P	DOM Aboveground Other	$y = 1E\text{-}07x^4 - 6E\text{-}05x^3 + 0.0134x^2 - 1.3619x + 77.914$
Boreal Plains	C-P	DOM Aboveground Litter	$y = -1E\text{-}07x^4 + 5E\text{-}05x^3 - 0.0085x^2 + 0.6384x + 49.022$
Boreal Plains	C-P	DOM Belowground Slow	$y = 0.0002x^2 - 0.0242x + 117.77$
Boreal Plains	C-P	DOM Belowground Fast	$y = 7E\text{-}08x^4 - 3E\text{-}05x^3 + 0.0056x^2 - 0.3622x + 9.3956$

Boreal Plains	C-P	DOM Belowground Very Fast	$y = -4E-06x^2 + 0.0019x + 1.7773$
Boreal Plains	MX-S	Aboveground Softwood	$y = -4E-11x^6 + 3E-08x^5 - 7E-06x^4 + 0.0009x^3 - 0.0615x^2 + 2.2731x$
Boreal Plains	MX-S	Aboveground Hardwood	$y = -8E-11x^6 + 5E-08x^5 - 1E-05x^4 + 0.0018x^3 - 0.1141x^2 + 3.3025x$
Boreal Plains	MX-S	Belowground Softwood	$y = -9E-12x^6 + 6E-09x^5 - 2E-06x^4 + 0.0002x^3 - 0.0137x^2 + 0.5046x$
Boreal Plains	MX-S	Belowground Hardwood	$y = -3E-11x^6 + 2E-08x^5 - 5E-06x^4 + 0.0006x^3 - 0.0391x^2 + 1.1018x$
Boreal Plains	MX-S	DOM Aboveground Other	$y = 1E-07x^4 - 6E-05x^3 + 0.014x^2 - 1.4938x + 89.516$
Boreal Plains	MX-S	DOM Aboveground Litter	$y = -2E-07x^4 + 1E-04x^3 - 0.0151x^2 + 1.038x + 66.725$
Boreal Plains	MX-S	DOM Belowground Slow	$y = 0.0003x^2 - 0.0352x + 152.66$
Boreal Plains	MX-S	DOM Belowground Fast	$y = 7E-08x^4 - 4E-05x^3 + 0.0059x^2 - 0.3845x + 10.415$
Boreal Plains	MX-S	DOM Belowground Very Fast	$y = -7E-06x^2 + 0.0016x + 1.8883$
Boreal Plains	MX-P	Aboveground Softwood	$y = -2E-11x^6 + 1E-08x^5 - 3E-06x^4 + 0.0005x^3 - 0.0329x^2 + 1.4752x$
Boreal Plains	MX-P	Aboveground Hardwood	$y = -6E-11x^6 + 4E-08x^5 - 1E-05x^4 + 0.0016x^3 - 0.1061x^2 + 3.2121x$
Boreal Plains	MX-P	Belowground Softwood	$y = -4E-12x^6 + 3E-09x^5 - 8E-07x^4 + 0.0001x^3 - 0.0073x^2 + 0.3275x$
Boreal Plains	MX-P	Belowground Hardwood	$y = -3E-11x^6 + 2E-08x^5 - 5E-06x^4 + 0.0006x^3 - 0.0377x^2 + 1.0865x$
Boreal Plains	MX-P	DOM Aboveground Other	$y = 1E-07x^4 - 6E-05x^3 + 0.0128x^2 - 1.3644x + 81.928$
Boreal Plains	MX-P	DOM Aboveground Litter	$y = -2E-07x^4 + 9E-05x^3 - 0.0148x^2 + 1.0618x + 57.509$
Boreal Plains	MX-P	DOM Belowground Slow	$y = 0.0002x^2 - 0.0316x + 139.79$
Boreal Plains	MX-P	DOM Belowground Fast	$y = 7E-08x^4 - 3E-05x^3 + 0.0053x^2 - 0.3491x + 9.422$
Boreal Plains	MX-P	DOM Belowground Very Fast	$y = -5E-06x^2 + 0.0014x + 1.8456$
Boreal Plains	D	Aboveground Softwood	$y = -9E-12x^6 + 6E-09x^5 - 1E-06x^4 + 0.0002x^3 - 0.0119x^2 + 0.4081x$
Boreal Plains	D	Aboveground Hardwood	$y = -7E-11x^6 + 5E-08x^5 - 1E-05x^4 + 0.0015x^3 - 0.0941x^2 + 3.3548x$

Boreal Plains	D	Belowground Softwood	$y = -2E-12x^6 + 1E-09x^5 - 3E-07x^4 + 4E-05x^3 - 0.0026x^2 + 0.0906x$
Boreal Plains	D	Belowground Hardwood	$y = -3E-11x^6 + 2E-08x^5 - 5E-06x^4 + 0.0006x^3 - 0.0361x^2 + 1.1232x$
Boreal Plains	D	DOM Aboveground Other	$y = 2E-07x^4 - 9E-05x^3 + 0.0172x^2 - 1.5466x + 79.802$
Boreal Plains	D	DOM Aboveground Litter	$y = -7E-08x^4 + 3E-05x^3 - 0.0047x^2 + 0.4199x + 56.971$
Boreal Plains	D	DOM Belowground Slow	$y = 0.0002x^2 - 0.0277x + 123.83$
Boreal Plains	D	DOM Belowground Fast	$y = 6E-08x^4 - 3E-05x^3 + 0.0049x^2 - 0.3131x + 8.2876$
Boreal Plains	D	DOM Belowground Very Fast	$y = -5E-06x^2 + 0.0014x + 1.7905$
Montane Cordillera	C-S	Aboveground Softwood	$y = 3E-11x^6 - 2E-08x^5 + 5E-06x^4 - 0.0005x^3 + 0.0128x^2 + 0.9961x$
Montane Cordillera	C-S	Aboveground Hardwood	$y = -4E-12x^6 + 3E-09x^5 - 7E-07x^4 + 0.0001x^3 - 0.0075x^2 + 0.2936x$
Montane Cordillera	C-S	Belowground Softwood	$y = 8E-12x^6 - 5E-09x^5 + 1E-06x^4 - 0.0001x^3 + 0.0029x^2 + 0.2211x$
Montane Cordillera	C-S	Belowground Hardwood	$y = -5E-12x^6 + 4E-09x^5 - 9E-07x^4 + 0.0001x^3 - 0.0077x^2 + 0.25x$
Montane Cordillera	C-S	DOM Aboveground Other	$y = 1E-07x^4 - 6E-05x^3 + 0.0129x^2 - 1.464x + 88.432$
Montane Cordillera	C-S	DOM Aboveground Litter	$y = 1E-08x^4 - 5E-08x^3 - 0.0014x^2 + 0.3691x + 31.971$
Montane Cordillera	C-S	DOM Belowground Slow	$y = 0.0004x^2 - 0.0654x + 99.417$
Montane Cordillera	C-S	DOM Belowground Fast	$y = 9E-08x^4 - 4E-05x^3 + 0.0071x^2 - 0.4583x + 11.11$
Montane Cordillera	C-S	DOM Belowground Very Fast	$y = -2E-05x^2 + 0.0074x + 1.4588$
Montane Cordillera	C-P	Aboveground Softwood	$y = -4E-11x^6 + 3E-08x^5 - 8E-06x^4 + 0.001x^3 - 0.0699x^2 + 2.7327x$
Montane Cordillera	C-P	Aboveground Hardwood	$y = -8E-12x^6 + 6E-09x^5 - 2E-06x^4 + 0.0002x^3 - 0.0159x^2 + 0.6103x$
Montane Cordillera	C-P	Belowground Softwood	$y = -1E-11x^6 + 6E-09x^5 - 2E-06x^4 + 0.0002x^3 - 0.0155x^2 + 0.6067x$
Montane Cordillera	C-P	Belowground Hardwood	$y = -8E-12x^6 + 6E-09x^5 - 1E-06x^4 + 0.0002x^3 - 0.0121x^2 + 0.3916x$
Montane Cordillera	C-P	DOM Aboveground Other	$y = 7E-08x^4 - 4E-05x^3 + 0.0111x^2 - 1.3509x + 86.692$

Montane Cordillera	C-P	DOM Aboveground Litter	$y = -7E\text{-}08x^4 + 4E\text{-}05x^3 - 0.0081x^2 + 0.7583x + 32.427$
Montane Cordillera	C-P	DOM Belowground Slow	$y = 0.0003x^2 - 0.0498x + 105.03$
Montane Cordillera	C-P	DOM Belowground Fast	$y = 8E\text{-}08x^4 - 4E\text{-}05x^3 + 0.0065x^2 - 0.4192x + 10.677$
Montane Cordillera	C-P	DOM Belowground Very Fast	$y = -6E\text{-}06x^2 + 0.0032x + 1.7631$
Montane Cordillera	MX-S	Aboveground Softwood	$y = -5E\text{-}12x^6 + 4E\text{-}09x^5 - 1E\text{-}06x^4 + 0.0002x^3 - 0.0218x^2 + 1.3375x$
Montane Cordillera	MX-S	Aboveground Hardwood	$y = -3E\text{-}11x^6 + 2E\text{-}08x^5 - 5E\text{-}06x^4 + 0.0007x^3 - 0.0468x^2 + 1.7432x$
Montane Cordillera	MX-S	Belowground Softwood	$y = -1E\text{-}12x^6 + 9E\text{-}10x^5 - 3E\text{-}07x^4 + 5E\text{-}05x^3 - 0.0048x^2 + 0.2969x$
Montane Cordillera	MX-S	Belowground Hardwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 3E\text{-}06x^4 + 0.0004x^3 - 0.0231x^2 + 0.7416x$
Montane Cordillera	MX-S	DOM Aboveground Other	$y = 1E\text{-}07x^4 - 6E\text{-}05x^3 + 0.013x^2 - 1.3265x + 78.041$
Montane Cordillera	MX-S	DOM Aboveground Litter	$y = -1E\text{-}07x^4 + 5E\text{-}05x^3 - 0.0087x^2 + 0.7965x + 36.192$
Montane Cordillera	MX-S	DOM Belowground Slow	$y = 0.0004x^2 - 0.0578x + 113.46$
Montane Cordillera	MX-S	DOM Belowground Fast	$y = 7E\text{-}08x^4 - 3E\text{-}05x^3 + 0.0057x^2 - 0.3681x + 9.6273$
Montane Cordillera	MX-S	DOM Belowground Very Fast	$y = -2E\text{-}05x^2 + 0.005x + 1.742$
Montane Cordillera	MX-P	Aboveground Softwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 4E\text{-}06x^4 + 0.0005x^3 - 0.0375x^2 + 1.5806x$
Montane Cordillera	MX-P	Aboveground Hardwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 4E\text{-}06x^4 + 0.0005x^3 - 0.0368x^2 + 1.4606x$
Montane Cordillera	MX-P	Belowground Softwood	$y = -5E\text{-}12x^6 + 3E\text{-}09x^5 - 8E\text{-}07x^4 + 0.0001x^3 - 0.0083x^2 + 0.3509x$
Montane Cordillera	MX-P	Belowground Hardwood	$y = -1E\text{-}11x^6 + 9E\text{-}09x^5 - 2E\text{-}06x^4 + 0.0003x^3 - 0.0205x^2 + 0.67x$
Montane Cordillera	MX-P	DOM Aboveground Other	$y = 8E\text{-}08x^4 - 5E\text{-}05x^3 + 0.0122x^2 - 1.4592x + 90.779$
Montane Cordillera	MX-P	DOM Aboveground Litter	$y = -1E\text{-}07x^4 + 5E\text{-}05x^3 - 0.01x^2 + 0.895x + 35.69$
Montane Cordillera	MX-P	DOM Belowground Slow	$y = 0.0004x^2 - 0.0586x + 113.44$
Montane Cordillera	MX-P	DOM Belowground Fast	$y = 8E\text{-}08x^4 - 4E\text{-}05x^3 + 0.0064x^2 - 0.4148x + 10.608$

Montane Cordillera	MX-P	DOM Belowground Very Fast	$y = -3E\text{-}06x^2 + 0.0026x + 1.7822$
Montane Cordillera	D	Aboveground Softwood	$y = -4E\text{-}12x^6 + 3E\text{-}09x^5 - 7E\text{-}07x^4 + 1E\text{-}04x^3 - 0.0072x^2 + 0.3202x$
Montane Cordillera	D	Aboveground Hardwood	$y = -4E\text{-}11x^6 + 3E\text{-}08x^5 - 7E\text{-}06x^4 + 0.0009x^3 - 0.0602x^2 + 2.3969x$
Montane Cordillera	D	Belowground Softwood	$y = -9E\text{-}13x^6 + 6E\text{-}10x^5 - 2E\text{-}07x^4 + 2E\text{-}05x^3 - 0.0016x^2 + 0.0711x$
Montane Cordillera	D	Belowground Hardwood	$y = -2E\text{-}11x^6 + 1E\text{-}08x^5 - 3E\text{-}06x^4 + 0.0004x^3 - 0.0276x^2 + 0.9071x$
Montane Cordillera	D	DOM Aboveground Other	$y = 1E\text{-}07x^4 - 7E\text{-}05x^3 + 0.0134x^2 - 1.2378x + 65.149$
Montane Cordillera	D	DOM Aboveground Litter	$y = -9E\text{-}08x^4 + 5E\text{-}05x^3 - 0.0095x^2 + 0.9392x + 36.225$
Montane Cordillera	D	DOM Belowground Slow	$y = 0.0004x^2 - 0.0613x + 113.71$
Montane Cordillera	D	DOM Belowground Fast	$y = 6E\text{-}08x^4 - 3E\text{-}05x^3 + 0.0045x^2 - 0.2881x + 7.6008$
Montane Cordillera	D	DOM Belowground Very Fast	$y = -1E\text{-}05x^2 + 0.003x + 1.7309$

Appendix B. Metadata

Age Layer

Layer
File name: abmi_age_up
File type: Vector Polygon Shapefile

Description
Data depicts the age of dissolved forest layers in the Upper Peace LUF planning region of Alberta

Credits
Alberta Biodiversity Monitoring Institute

Use Limitations
Data should not be used or distributed except for the advancement of the Ecosystem Services Assessment project, as contributed by Silvacom, Green Analytics, Alberta Innovates Technology Futures and Alberta Biodiversity Monitoring Institute

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_Transverse_Mercator
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983

Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Polygon
Object Count: 3,819,052 polygons

Strata layer

Layer
File name: abmi_strata_up
File type: Vector Polygon Shapefile

Description
Data depicts characteristics of dissolved forest strata layers in the Upper Peace LUF planning region of Alberta

Credits
Alberta Biodiversity Monitoring Institute

Use Limitations
Data should not be used or distributed except for the advancement of the Ecosystem Services Assessment project, as contributed by Silvacom, Green Analytics, Alberta Innovates Technology Futures and Alberta Biodiversity Monitoring Institute

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_Transverse_Mercator
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992

Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Polygon
Object Count: 1,987,993 polygons

Green and White zones layer

Layer
File name: alberta_green_white_zones_up
File type: Vector Polygon Shapefile

Description
Data depicts Green (forest) and White (agricultural) zones in the Upper Peace LUF planning region of Alberta

Credits
AltaLIS

Use Limitations
None

Geographic Extent
Upper Peace planning region of Alberta
West: -120.559516
East: -107.847855
North: 60.184845
South: 48.835066

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Polygon
Object Count: 17 polygons

Ecozones layer

Layer
File name: ecozones_up
File type: Vector Polygon Shapefile

Description
Data depicts two ecozones in the Upper Peace LUF planning region of Alberta; boreal plain and montane cordillera

Credits
Agriculture Canada

Use Limitations

None

Geographic Extent

Upper Peace planning region of Alberta

Spatial Reference Information

Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
  Semimajor Axis: 6378137.0
  Semiminor Axis: 6356752.314140356
  Inverse Flattening: 298.257222101

Spatial Data Properties

Data type: Vector
Geometry: Polygon
Object Count: 2 polygons

FMA layer

Layer

File name: fma_up
File type: Vector Polygon Shapefile

Description

Data depicts the forest management agreement (FMA) areas in the Upper Peace LUF planning region of Alberta

Credits

AltaLIS

Use Limitations

None

Geographic Extent

Upper Peace planning region of Alberta
West: -120.395354
East: -109.104198
North: 60.000381
South: 50.017684

Spatial Reference Information

Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties

Data type: Vector

Geometry: Polygon
Object Count: 19 polygons

FMU layer

Layer
File name: fmu_up
File type: Vector Polygon Shapefile

Description
Data depicts the forest management units (FMU) in the Upper Peace LUF planning region of Alberta

Credits
AltaLIS

Use Limitations
None

Geographic Extent
Upper Peace planning region of Alberta
West: -120.527991
East: -108.712868
North: 60.184845
South: 48.873433

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich

Datum: D_North_American_1983
Spheroid: GRS_1980
  Semimajor Axis: 6378137.0
  Semiminor Axis: 6356752.314140356
  Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Polygon
Object Count: 52 polygons

LUF layer

Layer
File name: luf_up
File type: Vector Polygon Shapefile

Description
Data depicts the Land Use Framework (LUF) area of the Upper Peace region of Alberta

Credits
AltaLIS

Use Limitations
None

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Polygon
Object Count: 1 polygon

Timber mills layer

Layer
File name: mills_up
File type: Vector Point Shapefile

Description
Data depicts the location of timber mills in the Upper Peace region of Alberta

Credits
Silvacom and Green Analytics

Use Limitations
Data should not be used or distributed except for the advancement of the Ecosystem Services Assessment project, as contributed by Silvacom, Green Analytics, Alberta Innovates Technology Futures and Alberta Biodiversity Monitoring Institute.

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0

False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
  Semimajor Axis: 6378137.0
  Semiminor Axis: 6356752.314140356
  Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector
Geometry: Point
Object Count: 10 points

Parks/protected areas layer

Layer
File name: protected_up
File type: Vector Polygon Shapefile

Description
Data depicts the area of protected land and parks in the Upper Peace LUF planning region of Alberta

Credits
AltaLIS

Use Limitations
Data should not be used or distributed except for the advancement of the Ecosystem Services Assessment project, as contributed by Silvacom, Green Analytics, Alberta Innovates Technology Futures and Alberta Biodiversity Monitoring Institute.

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information

Type: Projected

Projection: Transverse_Mercator

Projected Coordinate System:

NAD_1983_10TM_AEP_Forest

False Easting: 500000.0

False Northing: 0.0

Central Meridian: -115.0

Scale Factor: 0.9992

Latitude of Origin: 0.0

Linear Unit: Meter (1.0)

Geographic Coordinate System:

GCS_North_American_1983

Angular Unit: Degree

Prime Meridian: Greenwich

Datum: D_North_American_1983

Spheroid: GRS_1980

Semimajor Axis: 6378137.0

Semiminor Axis: 6356752.314140356

Inverse Flattening: 298.257222101

Spatial Data Properties

Data type: Vector

Geometry: Polygon

Object Count: 120 polygons

Indian Reserves layer

Layer

File name: reserves_up

File type: Vector Polygon Shapefile

Description

Data depicts Indian Reserves in the Upper Peace LUF planning region of Alberta

Credits

Geogratis

Use Limitations

None

Geographic Extent

Upper Peace planning region of Alberta

Spatial Reference Information

Type: Projected

Projection: Transverse_Mercator

Projected Coordinate System:

NAD_1983_10TM_AEP_Forest

False Easting: 500000.0

False Northing: 0.0

Central Meridian: -115.0

Scale Factor: 0.9992

Latitude of Origin: 0.0

Linear Unit: Meter (1.0)

Geographic Coordinate System:

GCS_North_American_1983

Angular Unit: Degree

Prime Meridian: Greenwich

Datum: D_North_American_1983

Spheroid: GRS_1980

Semimajor Axis: 6378137.0

Semiminor Axis: 6356752.314140356

Inverse Flattening: 298.257222101

Spatial Data Properties

Data type: Vector

Geometry: Polygon

Object Count: 7 polygons

Water buffers

Layer

File name: water_buffers_up

File type: Vector Polygon Shapefile

Description

Data depicts the buffer area surrounding hydrological features within the Upper Peace LUF planning region of Alberta. Buffers are as follows:

- Permanent lakes greater than 4 hectares were buffered 100m.

- Polygonal rivers were buffered 60m.
- Single line streams were buffered 30m either side.

Credits
Silvacom

Use Limitations
Data should not be used or distributed except for the advancement of the Ecosystem Services Assessment project, as contributed by Silvacom, Green Analytics, Alberta Innovates Technology Futures and Alberta Biodiversity Monitoring Institute.

Geographic Extent
Upper Peace planning region of Alberta

Spatial Reference Information
Type: Projected
Projection: Transverse_Mercator

Projected Coordinate System:
NAD_1983_10TM_AEP_Forest
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -115.0
Scale Factor: 0.9992
Latitude of Origin: 0.0
Linear Unit: Meter (1.0)

Geographic Coordinate System:
GCS_North_American_1983
Angular Unit: Degree
Prime Meridian: Greenwich
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Spatial Data Properties
Data type: Vector

Geometry: Polygon
Object Count: 11,520 polygons