Carbon Profile Analysis Report

MARTEL MAGPIE FOREST

Version 1.0

April 15, 2020

Project 1556-1

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- Joseph Pallant, Director of Climate Innovation, Ecotrust Canada.
- Don Bazeley, RPF, Divisional Forester, Chief Foresters Group – Ontario, RYAM Forest Management.
- Tom Moore, Spatial Planning Systems.
- Michael Magnan, Carbon Accounting Team, Victoria, BC.
- Sarah Sullivan, RPF, Planning Superintendent – North Ontario East, RYAM Forest Management.

Heather Tumber (Forsite) and Cosmin Man, RPF (Forsite) completed this work under the supervision of Cam Brown, RPF (Forsite).

Executive Summary

Ecotrust Canada is a charity with the goal of building resilient economies in rural, remote, and Indigenous communities. Under the climate innovation initiative, Ecotrust Canada has requested Forsite to conduct a carbon (C) profile analysis for the Martel-Magpie Forest (MMF). The MMF (ON Management Unit 509 and 565) is located in the Boreal Shield East terrestrial ecozone and covers an area of ~1.63 million ha. The non-forested land base was estimated to ~230,000 ha (14.2%) and the forested land base to 1.40 million ha (~326,000 ha (20.0%) unavailable for harvesting (unmanaged) and ~1.07 million ha (65.8%) available for harvesting (managed)).

This analysis considered 3 scenarios over a 150 year time horizon: (1) RAYAM's most recent long term management direction (LTMD) – currently under review by the ON Ministry of Natural Resources and Forestry, (2) LTMD + hold 10% more growing stock on the landbase and (3) LTMD + hold 20% more growing stock on the landbase. The analysis was conducted using a modelling framework that included a forest estate model (Patchworks) to develop a harvest schedule subject to a range of forest management objectives, a carbon budget model (CBM-CFS3) to simulate the forest carbon dynamics within the forest ecosystem using the disturbance schedules determined by the forest estate model, and a harvested wood products (HWP) model (CBM-FHWP) to simulate the C storage and emission dynamics within HWP. A Verified Carbon Standard (VSC) methodology (VM0012) was used to estimate industrial emissions for harvesting, transport of logs, and manufacturing.

The results indicated that the MMF continues to be a C sink under the LTMD scenario for the duration of the 150 year planning horizon (+5.1% more C stored at 150 years in the future). While the C stored within the forest ecosystem declined slightly over time, the C stored in harvested wood products increased enough to compensate for the C loss in the forest ecosystem. The two alternate 'project' scenarios analyzed here indicated that the net incremental difference (i.e., the net C benefits) compared to the LTMD can accumulate ~179,000 tCO_2e over 150 years in the case of 10% more growing stock, and ~8.63 million tCO_2e in the case of 20% more growing stock.

The GS20 scenario would appear to offer the best option for a carbon offset project as it generates considerable C benefits in the first 4 decades (10.2 million t CO2e), and then produces a wide fluctuation of gains and losses after that point (period 5-15 total -1.6 million t CO2e). Thus a plausible scenario would look like selling ~5-8 million credits over the first 30-40 years (less insurance/leakage discounts) and then no further credits would be sold.

Incremental Carbon Stored or Emitted in each period relative to the LTMD scenario (Gross C Benefit/period)

Period (yrs)	GS10 (tCO2e)	GS20 (tCO2e)
1-10	-1,206,398	-298,796
11-20	13,924	1,672,085
21-30	1,523,333	3,307,047
31-40	2,545,753	5,567,293
41-50	-189,079	1,013,490
51-60	-105,078	461,007
61-70	-117,993	-684,384
71-80	-1,341,101	-1,298,016
81-90	-325,403	263,143
91-100	1,575,019	1,803,306
101-110	190,446	81,744
111-120	18,513	433,516
121-130	-729,885	-1,365,486
131-140	-2,295,532	-2,784,647
141-150	623,057	461,595
Total	**179,577**	**8,632,898**

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Document Revision History

Version	Date	Description
1.0	April 15, 2020	Detailed assumptions for C models and results for LTMD, and two alternate scenarios (10% and 20% increase in managed growing stock)

Acronyms

CBM-CFS3	Carbon Budget Model for the Canadian Forest Sector
CBM-FHWP	Carbon Budget Model for the Forest Harvested Wood Products
DOM	Dead Organic Matter
GHG	Greenhouse Gas
GWP	Global Warming Potential
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
LTMD	Long Term Management Direction
MMF	Martel Magpie Forest
VCS	Verified Carbon Standard
CO_2e	Carbon Dioxide Equivalent
t	Metric tonnes

1 Introduction

Ecotrust Canada is a charity with the goal of building resilient economies in rural, remote, and Indigenous communities. Since 2019, Ecotrust Canada started four strategic initiatives, one of which is climate innovation. Under the climate innovation initiative, Ecotrust Canada has requested Forsite to conduct a carbon (C) profile analysis for the Martel-Magpie Forest (MMF). This document details the C profile analysis assumptions and the results with reference to the forest estate modeling conducted by Forsite in developing the most recent long term management direction (LTMD)[1] for RYAM Forest Management.

2 Methods

2.1 SCENARIOS

The scenarios modelled in this analysis are detailed in Table 1. The harvest rates and managed growing stock (i.e., volume on the working landbase) are compared in Figure 1. The forest estate model was asked to increase the growing stock while minimizing impact on harvest levels, and in the case of GS10 scenario, it was able to accomplish this with only a relatively small harvest impact (-9.5%) in the first 80 years and almost no harvest impact in the long-term. Holding 20% more GS on the land base (i.e., GS20 scenario) caused a more significant and sustained reduction in harvest levels (16.8% in the short-term and 9.6% in the long-term).

Table 1 Scenarios Description

Scenario ID	Description
V1_MMF_LTMD_5	The approved LTMD scenario. Clearcut with Reserves, Slash left to decay (not burnt)
V1_MMF_GS10	Based off LTMD, managed standing volume was increased by up to 10% by the end of the 150-year planning horizon
V1_MMF_GS20	Based off LTMD, managed standing volume was increased by up to 20% by the end of the 150-year planning horizon

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[1] Currently under public review: https://www.efmp.lrc.gov.on.ca/eFMP

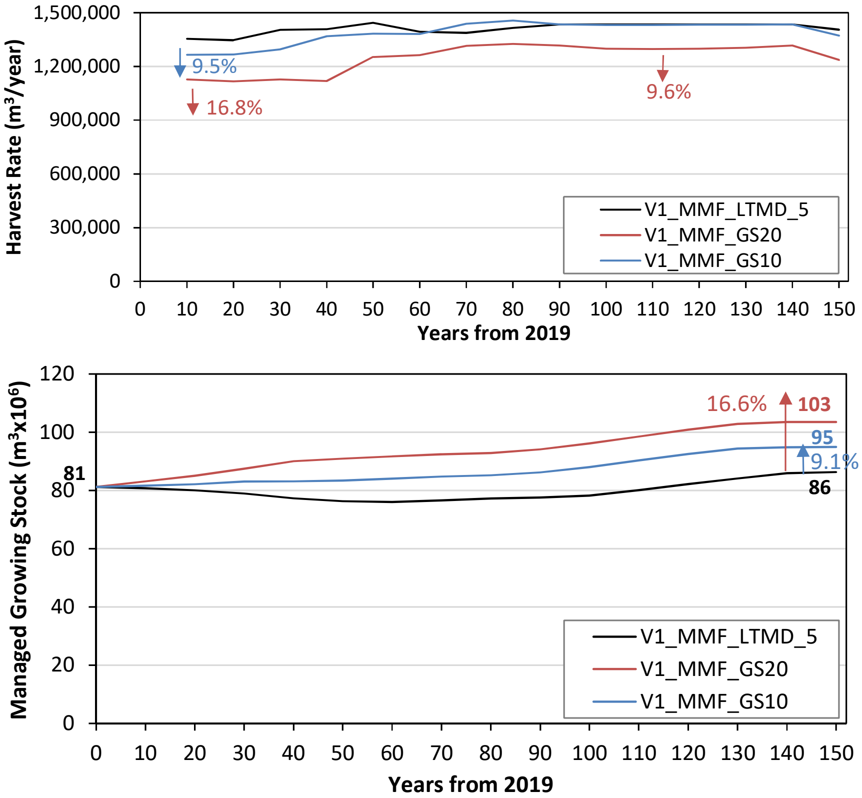


Figure 1 Comparing Harvest Rates (top) and Managed Growing Stock (bottom) for all Scenarios

The boreal forest region where the MMF is located is driven primarily by the dynamics of softwood stand types. Natural stand dynamics in this region of the boreal forest drives older hardwood stands toward mixed-wood and softwood stands. Consequently, the policy direction in the region drives the land base management towards creating mature and old softwood stand types. It follows that the industry focus in the MMF is on harvesting softwood stand types. These polices were reflected in the forest estate model. Thus, the additional managed growing stock achieved in the two alternate scenarios was biased toward softwood stands (Figure 2). This is an important finding given the C dynamic differences between the two stand types.

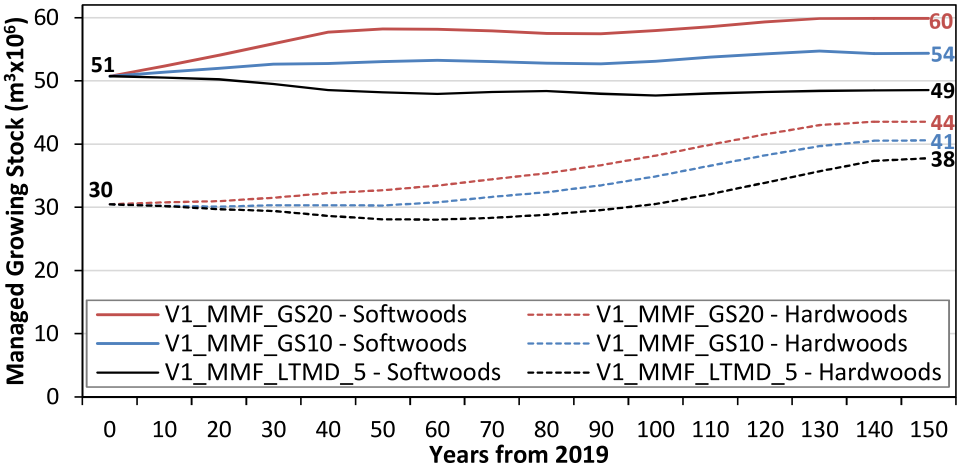


Figure 2 Comparing Managed Growing Stock by Species Components for All Scenarios

In all three scenarios, the forest estate model attempted to achieve many objectives that were calibrated and explored during the extensive analysis that occurred previously to developing relatively well- balanced LTMD. These objectives included short-term spatial objectives (texture, pattern, harvest patch openings, and moose emphasis areas) and long-term objectives (landscape-level objectives for Boreal Landscape Guide (BLG) indicators, economic indicators, silviculture renewal limits, and transportation expenditures). The already complex objectives matrix was updated with 10% and 20% more managed growing stock objectives for the two alternate scenarios.

It was observed that the forest estate model found it difficult to develop similar balanced harvest strategies between the two alternate scenarios. In the case of the GS10 scenario, the forest estate model was able to build up and retain the additional 10% managed growing stock by making subtle changes to the LTMD scenario (area harvested, age of harvest - Figure 3). The forest estate model initially reduced the area and volume harvested and gradually recovered to a similar long-term harvest volume. The 10% additional growing stock did not require the forest estate model to undergo substantial changes. In the +20% growing stock scenario, the forest estate model had to undergo more substantial and sustained changes by reducing the harvest area (-13% initially) and volume (-16.8% initially) over the planning horizon. This resulted in a generally older forest on the landbase and the harvesting of slightly older, higher volume/ha stands in the future.

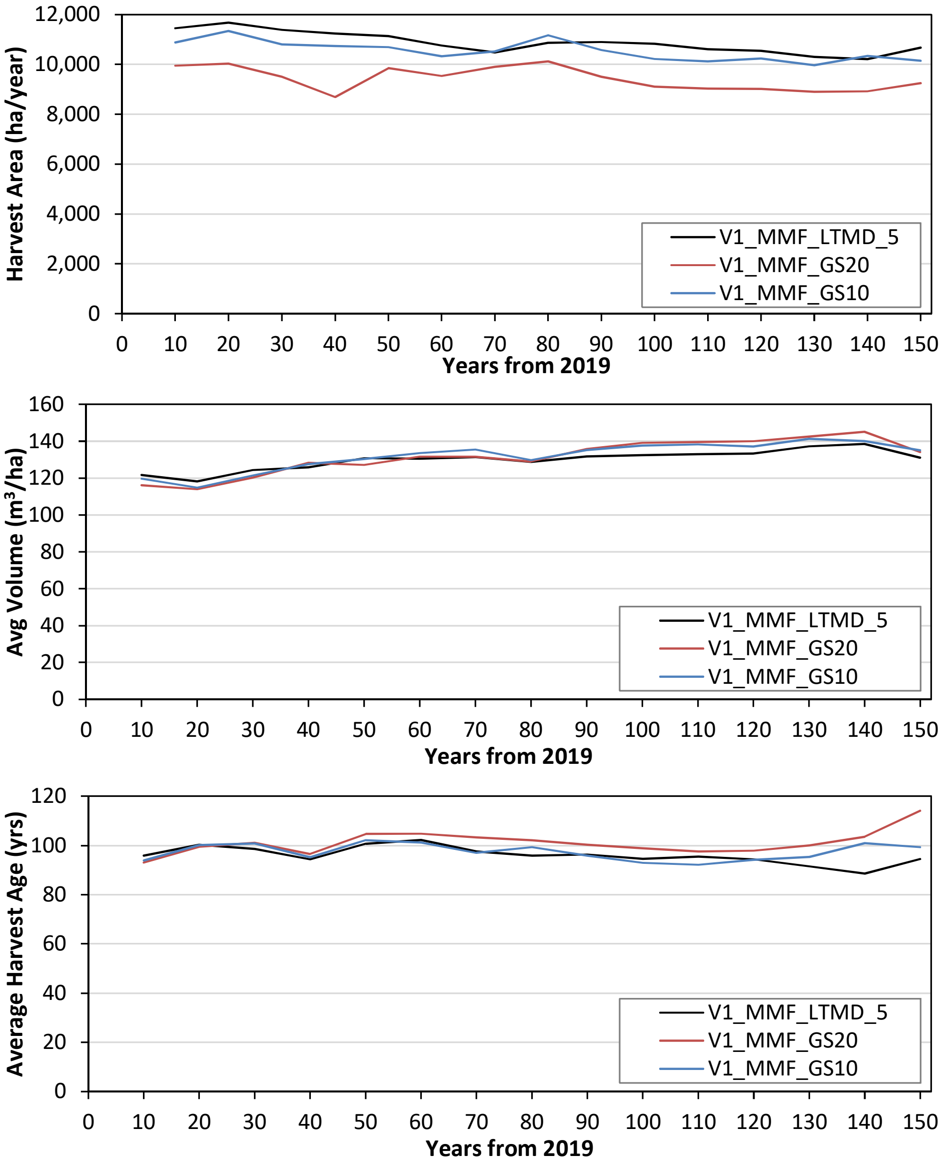


Figure 3 Comparing Harvest Area, Average Harvest Volume and Age for All Scenarios

2.2 CARBON STORAGE AND GHG EMISSIONS WITHIN THE FOREST ECOSYSTEM

Carbon dynamics within forest ecosystems are complex and determined by many factors. To address this issue the Canadian Forest Service developed the CBM-CFS3 model (Kurz, et al., 2009) and it has undergone significant testing and verification since then via numerous peer-reviewed published papers and technical reports. The CBM-CFS3 uses age-volume yield curves to estimate C in live biomass and an iterative process based on the inventory, historical, and last stand-replacing disturbances to initiate the dead organic matter (DOM) pools. The CBM-CFS3 is used by the Canadian government to estimate and report the C storage and greenhouse gas (GHG) emissions of Canadian forests under international agreements.

For the purpose of this analysis, the CBM-CFS3 model was used to estimate C storage and GHG emissions within the forest ecosystem. The type and extent of harvest disturbances and natural succession for the scenarios outlined in section 2.1 were determined in a timber supply analysis conducted in Patchworks (Spatial Planning

Systems). The harvest schedule was transferred along with the inventory, yield curves, and transition rules into CBM-CFS3 where the C storage and GHG emissions within the forest ecosystem were estimated.

The harvested C reported by CBM-CFS3 was then passed to the CBM-FHWP module to estimate the C storage and GHG emissions from harvested wood products over time.

2.1 DESCRIPTION OF THE FOREST ESTATE

The MMF (ON Management Unit 509 and 565) located in the Boreal Shield East terrestrial ecozone covers an area of ~1.63 million ha (Figure 4). The non-forested land base was estimated to ~230,000 ha (14.2%) and the forested land base to 1.40 million ha. Approximately 326,000 ha (or 20.0%) of the forested land base is unavailable for harvesting and considered unmanaged, while approximately 1.07 million ha (or 65.8%) of the forested land base is available for harvesting and considered managed.

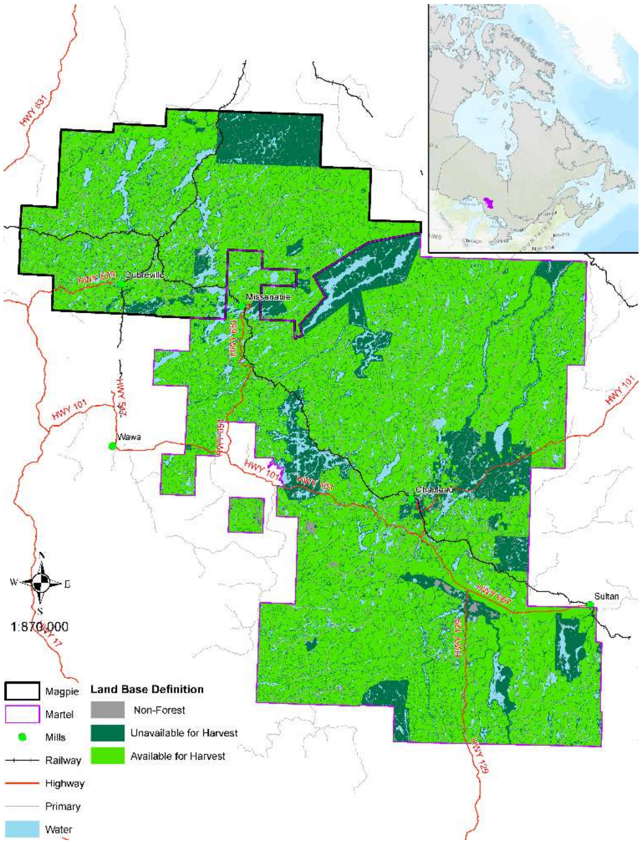


Figure 4 Location of Martel-Magpie Forest

The forested land base is covered by conifer dominated stands (~679,000 ha), hardwood dominated stands (~398,000 ha), and mixed stands (~313,000 ha) (Figure 5). Most of the forested land base is currently found in age classes 20-99 years indicating a relatively active ecosystem with many natural and anthropogenic disturbances (Figure 6). Consequently, the area available for harvesting is covered in most part by stands 20-99 years of age in a relatively well balanced mix of species (conifers and hardwoods) (Figure 7).

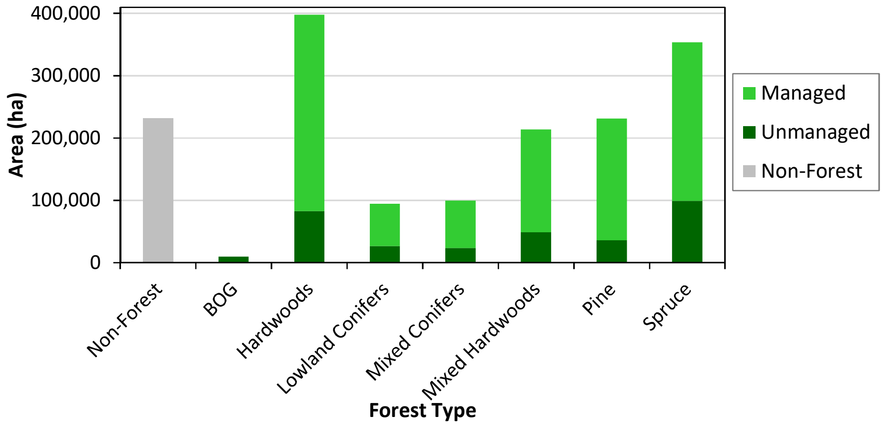


Figure 5 Area Distribution by Land Base Definition

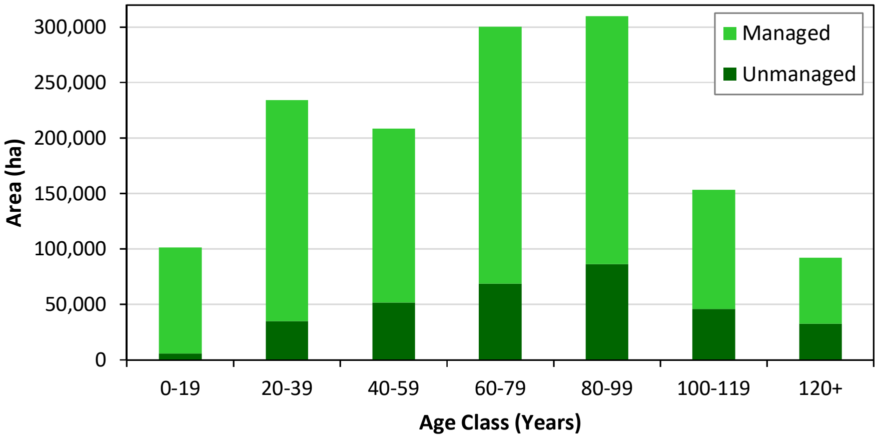


Figure 6 Forested Area Distribution by Age Class

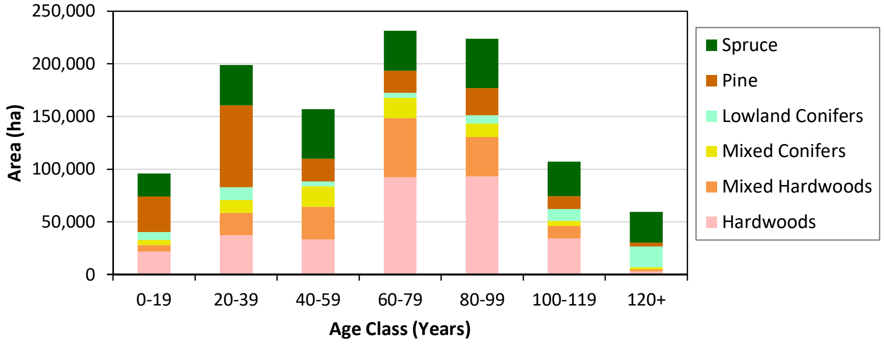


Figure 7 Managed Area Distribution by Age Class and Species Groups

2.1.1 INPUT DATA ASSUMPTIONS

The MMF overlaps entirely with the Boreal Shield East terrestrial ecozone. The default CBM-CFS3 values for annual average temperature and precipitation were used in this analysis (Table 2). The effect of climate change on C storage and GHG emissions was not modeled.

Table 2 Climate values for MMF

Terrestrial Ecozone	Annual Average Temperature (°C)	Annual Average Precipitation (mm)
ON Boreal Shield East	2.05	873

Dead Organic Matter (DOM) turnover parameters refer to the turnover rates of live biomass into respective DOM pools specific for each terrestrial ecozone (Table 3). The values used in this analysis are default model parameters supported by an exhaustive literature review (e.g., (Johnson, 1992)).

Table 3 DOM Turnover Parameters

Ecozone	Parameter	Default Value
ON Boreal Shield East	Average; Slow DOM Pool	0
	Average; Decay Multiplier	1
	Average; Stand-Replacing Disturbance Interval (years)	125
	Turnover Rate; Softwood Branch	0.04
	Turnover Rate; Hardwood Branch	0.04
	Turnover Rate; Stem Annual	0.005
	Snag Fall Rate; Softwood Stem	0.032
	Snag Fall Rate; Softwood Branch	0.1
	Snag Fall Rate; Hardwood Stem	0.032
	Snag Fall Rate; Hardwood Branch	0.1
	Foliage Fall Rate; Softwood	0.1
	Foliage Fall Rate; Hardwood	0.95

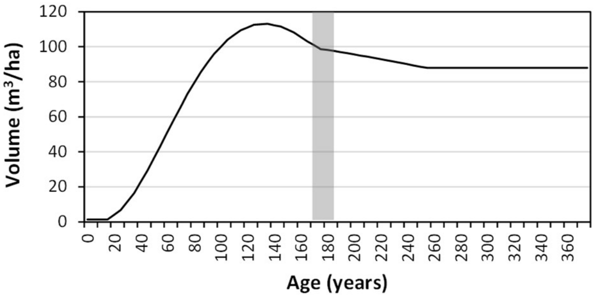
The CBM-CFS3 uses 27 parameters and a complex system of equations to convert the age-volume yields into biomass C separated into various components (e.g., stemwood, branches, tops, foliage etc.). Hardwood and softwood stands are treated differently. The parameter values were developed from over 1,000 regression equations compiled from over 133,000 permanent sample plot data across Canada (more than 11 million tree measurements). No changes were made to the default CBM-CFS3 parameters. The age-volume yields used in this analysis met the required CBM-CFS3 merchantable criteria (Table 4).

Table 4 Criteria for Merchantable Yield Curves

Province	Stump Height (cm)	Top Diameter (cm)	Minimum Diameter at Breast Height (cm)
Ontario	30	7.0	9.0

In the forest estate model, the merchantable volume yield curves decline following a peak value in order to simulate volume loss as stands break-up from old age. This decline in merchantable volume is appropriate for predicting harvest volumes but may underestimate live biomass C at certain times in the cycle. The top 4 largest area yield curves are included in Figure 8 to illustrate the potential impact of natural succession on C storage.

289-managed-LC1-PRSNT-Sb (36,189 ha)



497-unmanaged-OH1-PRSNT-Bw (26,253 ha)

168-managed-BW1-PRSNT-Bw (25,100 ha)

1-managed-MH1-PRSNT-Po (22,428 ha)

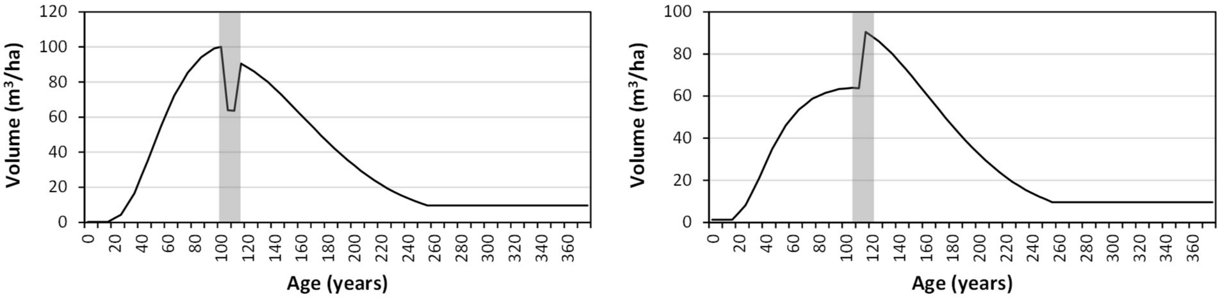


Figure 8 Yield Curves Examples (Grey Shaded Area Indicates Break-up Age)

Understanding differences in C dynamics for hardwoods and softwoods in CBM-CFS3 is critical when interpreting results. To illustrate how the merchantable yield curves translate into C components, the largest area yield curve (i.e.,289-managed-LC1-PRSNT-Sb) has been used as an example. Here, the yield curve was used to create two separate CBM-CFS3 stand-alone projects, in one the yield curve was assumed 100% composed of softwoods, and in the other 100% composed of hardwoods. Upon creating the CBM-CFS3 projects, the C components indicated slightly higher C for hardwoods with the same m³/ha, mostly because the hardwoods had more Other C (Figure 9). The Other C includes branches, sapling and submerchantable stem wood (including associated bark), and tops and stumps of merchantable trees (including the associated bark). The difference in Other C is explained by the fact that for the same merchantable volume, hardwood species store more C in branches than softwoods. Recall, CBM-CFS3 uses a complex system of equations to convert the age-volume yields into biomass C which are different for softwoods and hardwoods. The foliage C difference is explained by the seasonal loss of foliage that hardwood species experience, yet this difference is relatively small relative to total C.

These two separate CBM-CFS3 projects were run over 150-year planning horizon with no disturbances (Figure 10). The results indicated that, initially, the softwoods had a visibly higher total C stored in the forest ecosystem (i.e., biomass + dead organic matter (DOM)). However, by year 60, the hardwoods stored more total C than softwoods and continued to increase in favour of hardwood to the end of the 150 year planning horizon.

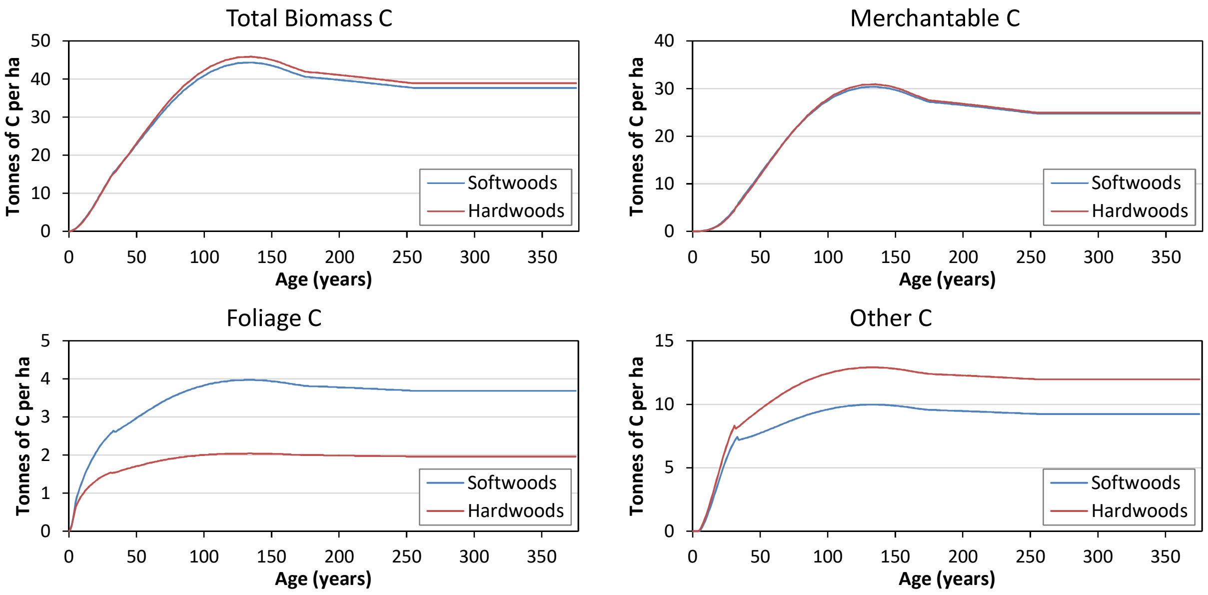


Figure 9 Comparing C Components of the Same Yield Curve Assumed as 100% Softwood and 100% Hardwood in Two Separate CBM-CFS3 Projects

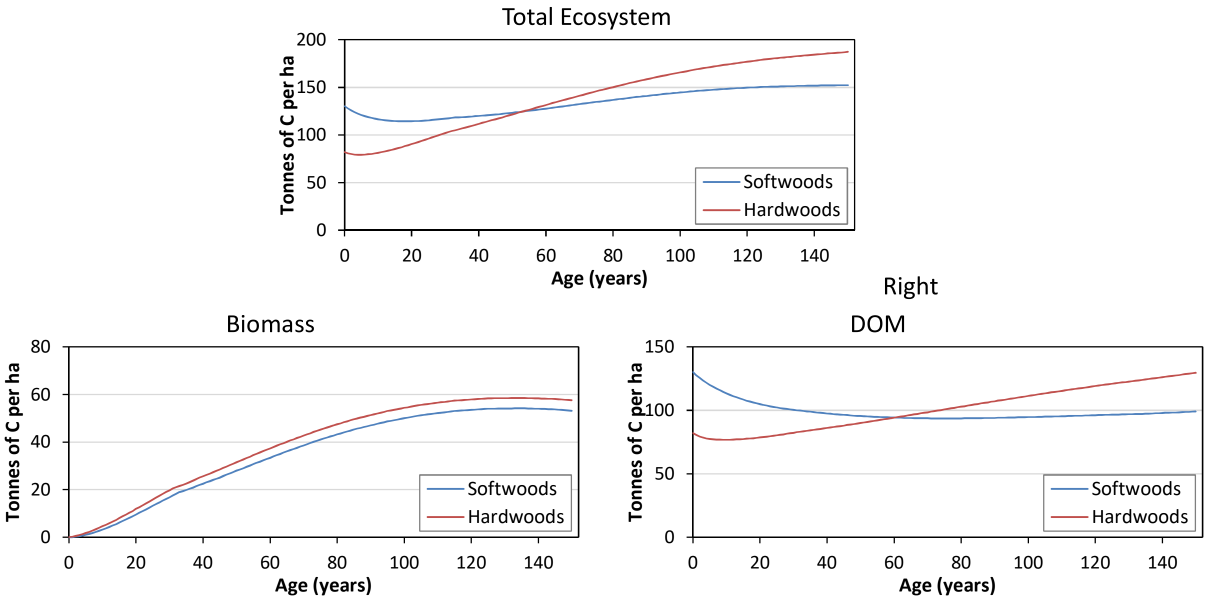


Figure 10 Comparing C Outputs of the Same Yield Curve Assumed as 100% Softwood and 100% Hardwood in Two Separate CBM-CFS3 Projects

2.1.2 MODEL INITIALIZATION / HISTORIC DISTURBANCES

The historic and last stand-replacing disturbances are essential for initializing the amount of C in DOM pools. The CBM-CFS3 model uses an iterative process that simulates the historic stand-replacing disturbance at regular intervals for long periods of time (e.g., grow, burn, grow, burn or grow, cut, grow, cut etc.) until the difference between two successive intervals is less than 1%. Then, the last stand-replacing disturbance is simulated and the stand is grown to the current age in the inventory. The last stand-replacing disturbance was set to fire except where inventory records indicated harvest was the last stand-replacing disturbance.

2.1.3 WILDFIRE DISTURBANCES

There were no fire disturbances modeled in this analysis.

2.1.4 SUCCESSION

The Patchworks forest estate model was set-up such that natural succession occurred automatically at the break-up age. Within the forested area not available for harvesting (i.e., unmanaged), the automatically set natural succession occurred unimpeded, whereas in the forested area available for harvesting (i.e., managed) the forest estate model had to find a harvest schedule given the natural succession break-up ages. Because the Patchworks yields already had built-in natural succession, there was no need to simulate natural succession events in CBM-CFS3.

2.1.5 HARVEST EVENTS

Harvest events (clearcuts) are disturbance events that transfer a portion of the live biomass into the forest product sector. For the modelled scenarios of MMF, 100% of the merchantable C was transferred to the forest sector (i.e., Harvested Wood Products (HWP)). The non-merchantable C was left on site to decay and none of it was burned. The CBM-CFS3 disturbance matrix was manually adjusted to reflect the aforementioned assumptions (Table 5).

Table 5 MMF Disturbance Matrix for Harvest Events

From C Pool	To C Pool	Fraction of C transferred
Swd/Hwd Merchantable	Products	1
Swd/Hwd Foliage	AG Very Fast DOM	1
Swd/Hwd Other*	AG Fast DOM	1
Swd/Hwd Coarse Roots	AG Fast DOM	0.5
	BG Fast DOM	0.5
Swd/Hwd Fine Roots	AG Very Fast DOM	0.394
	BG Very Fast DOM	0.61
Swd/Hwd Stem Snag	Medium DOM	1
Swd/Hwd Branch Snag	AG Fast DOM	1
AG Very Fast DOM	AG Very Fast DOM	1
BG Very Fast DOM	BG Very Fast DOM	1
AG Fast DOM	AG Fast DOM	1
BG Fast DOM	BG Fast DOM	1
Medium DOM	Medium DOM	1
AG Slow DOM	AG Slow DOM	1
BG Slow DOM	BG Slow DOM	1

** branches, sapling and submerchantable stem wood (including associated bark), and tops and stumps of merchantable trees (including the associated bark)*

2.1.6 QUANTIFICATION OF CARBON STORAGE AND GHG EMISSIONS

The CBM-CFS3 model directly reports the annual C stocks stored in each pool. It reflects and accounts for:

1) All losses and all gains due to gas exchanges (autotrophic and heterotrophic respiratory processes) between the forest ecosystem and the atmosphere,
2) All losses due to natural disturbances, and
3) All losses due to harvesting events and emissions from slash burning.

Outputs are provided in metric tonnes of C and converted to tonnes of carbon dioxide equivalent or tCO_2e (Eq. (1)). This is necessary to integrate gasses with different global warming potential (GWP) values into the assessment. For example, methane (CH_4) is 28 times more damaging to the atmosphere on a per unit weight basis than CO_2 (CO_2 and CO have a GWP of 1). CO is assumed to be rapidly oxidized to CO_2 and assumed to be CO_2 to start with (Stinson, et al., 2011). The emissions of GHGs with the GWP >1 (CH_4 and N_2O), labeled here as non-C emissions, need to be converted to tCO_2e. The CH_4 emissions reported by CBM-CFS3 in tC are used in Eq. (1) to convert to CO_2e. The CBM-CFS3 does not track nitrogen dynamics, thus as a proxy, a factor of 0.00017 of the CO_2 generated from wildfires and slash burning is applied to determine the GHG emissions attributed to N_2O (Kurz, et al., 2009) and then Eq.(1) is used to convert to tCO_2e.

$$tCO_2e = tC * MW * GWP \tag{1}$$

where,

tCO_2e is the value in tonnes of CO_2e,

tC is the value in tonnes of C,

MW is the molecular weight of the gas type (44/12 for CO_2, 16/12 for CH_4), and

GWP is the 100-year global warming potential for the gas type (1 for CO_2, 28 for CH_4, and 265 for N_2O from 5th assessment of the IPCC (www.ipcc.ch))

2.2 CARBON STORAGE AND GHG EMISSIONS DURING THE PRODUCTS LIFE CYCLE

The harvested C from the forest ecosystem is not immediately released to the atmosphere, but it is stored in a mix of forest products, some of it for many decades. The mix of products created from the harvested C varies with forest region, timber quality, and market demands. The forest products life cycle is difficult to track in all countries, but recently, especially in North America, methodologies to track forest products C storage have emerged in an effort to comply with international binding agreements.

The C storage and the GHG emissions in the forest products life cycle were tracked with the CBM-FHWP module developed by the Carbon Accounting Team, Victoria, BC (office leader, Werner Kurz). The Carbon Accounting Team expert (Michael Magnan) worked with Forsite to develop a custom model for the MMF. The custom model included every aspect of tracking C storage and GHG emissions associated with decay, combustion for bioenergy (e.g., hog fuel), landfill decomposition, and methane treatment (flaring, capture, or direct release to the atmosphere). Similarly to the CBM-CFS3, the outputs from CBM-FHWP are in tC; these were converted to tCO_2e using Eq. (1).

The CBM-FHWP model uses an exponential decay curve based on the half-life of a wood product (years until 50% of the pool is oxidized). For this analysis, all HWP were assumed to be used within North America with default CBM-FHWP parameters: half-life for long-lived products was 35 years (25 years for panels) and 2 years for short-lived products, and once in landfill, the half-life for degradable wood products was 29 years, and 14.5 years for degradable paper. It was assumed that all HWP ended in municipal solid waste landfills that had methane flaring technologies.

The mix of primary products produced from harvesting in MMF is as follows (from Don Bazeley, RPF, Divisional Forester, Chief Foresters Group – Ontario, RYAM Forest Management):

- Softwood: 35% of harvested C stored in long-lived products (29% lumber and 6% medium density fibreboard), 41% in short-lived products (pulp and paper), and 24% used as industrial bioenergy.
- Hardwood: 86% of harvested C stored in long-lived products (70% oriented strand board, 10% veneer, and 6% medium density fibreboard) and 14% used as industrial bioenergy.

The GHG emissions related to harvesting activities, log transport, and manufacturing are relatively small. However, for large areas such as MMF, these GHG emissions should be accounted for to be in line with the conservative approach essential to C accounting. The Verified Standard Carbon (VCS) methodology VM0012 (VCS methodology for IFM projects in Temperate and Boreal Forests, at www.v-c-s.org) provides a framework and assumptions that can be used to quantify the emissions from harvesting activities, transport of log, and manufacturing. In case of the MMF, the coefficient assumptions used to estimate the industrial GHG emissions based on harvested C are shown in Table 6. The average hauling distance was determined from the forest estate model outputs to four different destinations.

Table 6 Industrial GHG Emissions Assumptions (VM0012)

GHG Emission Source	Product Class	Coefficient (VM0012) (tC emitted / tC raw material)
Harvesting	All	0.016

Transport of logs (per average hauling distance of 114 km)	All	0.00007
Manufacturing	Sawnwood	0.04
	Chemical Pulp	0.13

2.3 QUANTIFICATION OF C-PROFILES

The **Net C** for each scenario is calculated at each time step as the C storage (within the forest ecosystem and in the HWP) less GHG emissions (non-C emissions as CH_4 and N_2O within the forest ecosystem and the GHG emissions associated with harvesting, transporting, manufacturing, decaying, and combustion of the harvested C). The Net C-profiles give indication in each time step about the C status of the forest (sink vs. source).

The **Net Incremental Difference** (i.e., additional C stored) relative to the V1_MMF_LTMD_5 (Business as usual (BAU)) scenario is also quantified in this analysis using Eq. (2). The Δ_i indicates the performance in terms of C of the scenario of interest relative to the BAU.

$$\Delta_i = (SCN_i - SCN_{i-1}) - (BAU_i - BAU_{i-1}) \quad (2)$$

where,

SCN – total C for the scenario of interest

BAU – total C for the baseline (V1_MMF_LTMD_5)

i – time step

3 Results

3.1 LONG TERM MANAGEMENT DIRECTION

The LTMD shows that initial Net C of ~769 million tCO_2e increased slightly over time to ~808 tCO_2e (+5.1%) by the end of the 150-year planning horizon meaning that the MMF under the LTMD continues to be a C sink. (Figure 11). The vast majority of C was stored in the forest ecosystem which declined slowly over time, and by the end of the planning horizon it was 9.4% lower than the initial value. Within the forest ecosystem, the vast majority of C was stored by the managed area of the land base because it covered the largest portion of the forest estate. The C stored in HWP increased over time to a high of ~115 million tCO_2e by the end of the planning horizon. The gradual increase of C stored in HWP compensated for the C decline observed in the forest ecosystem. The emissions related to disturbances (i.e., assumed zero emissions as no fire or burning was simulated), industrial activities (harvesting, transportation, and manufacturing), and HWP stored in landfills accounted for a very small fraction of the Net C (<0.1%).

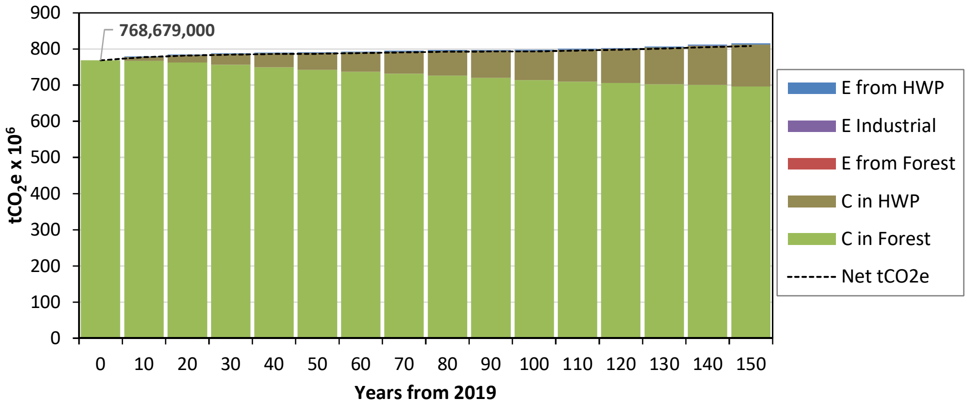


Figure 11 V1_MMF_LTMD_5 Net C Profile. M, managed, U, unmanaged, E, emissions.

Within the forest ecosystem, the largest portion of C was stored in soil (47%) and litter (22%), while the above-ground biomass (i.e., the C stored in actual trees, which can be directly managed via forest management activities) accounted for 18% (Figure 12). Deadwood and below-ground biomass accounted for the remaining C stored within the forest ecosystem. Note that the above-ground biomass within the managed portion of the land base accounted for 13%, leaving the unmanaged above-ground biomass to 5%.

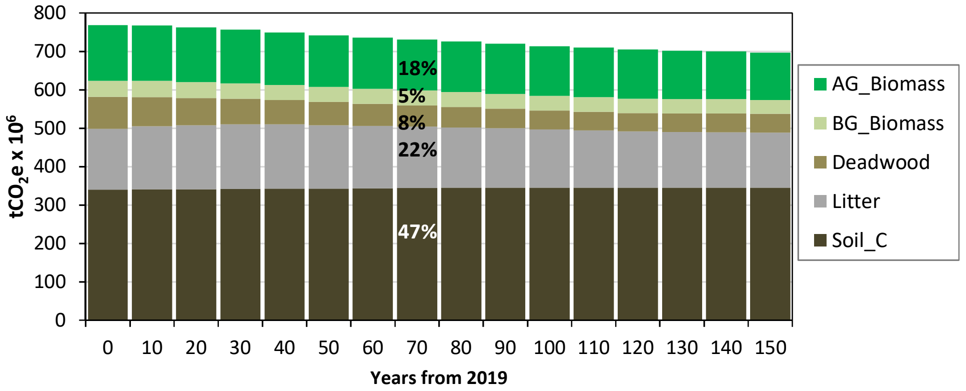


Figure 12 V1_MMF_LTMD_5 Forest Ecosystem C Profile. AG, above-ground, BG, below-ground.

Currently, the forested area is relatively well distributed over the age classes, indicating a dynamic ecosystem with frequent stand-replacing disturbances (Figure 13). By the end of the 150-year planning horizon, the managed portion of the land base becomes more or less regulated, with the vast majority of it (76%) being relatively equally distributed in age classes younger than 80 years. The unmanaged portion of the land base was not disturbed by stand replacing events and it continued to grow over time. A key observation was the distribution of C stocks within the forest ecosystem (in tC/ha) over the age classes. Here, two peaks were reached, one within age classes 80-120 years and the other over 180 years. However, the variation of C stocks over age classes changed between various time steps because of the succession rules imposed in the forest estate model. Recall, the natural succession was embedded into the yield curves within the forest estate model, and following natural succession at break-up age, a stand could transition to a yield curve that could have been vastly different from the original yield curve. Therefore, the C stored within the forest ecosystem varied unpredictably over the planning horizon as the forest estate model attempted to balance the harvest events with potential loss of volume from embedded natural succession.

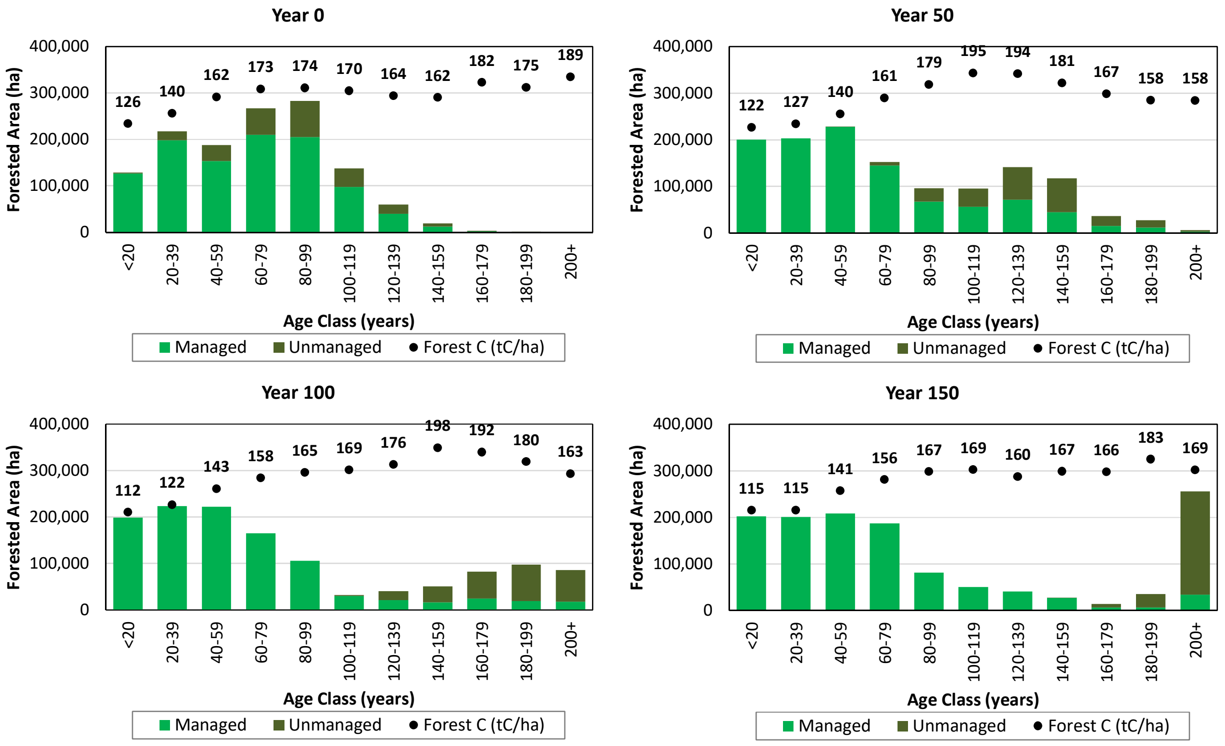


Figure 13 V1_MMF_LTMD_5 Area and C within Forest Ecosystem by Age Class

3.2 GROWING STOCK INCREASE

Relative to scenario V1_MMF_LTMD_5, when the managed growing stock was increased by up to 10%, the Net C increased little by the end of the 150-year planning horizon (Figure 14). When the managed growing stock was increased by 20%, the Net C increased by 1.1% by the end of the 150-year planning horizon. It was observed that the scale of growing stock increase did not translate accordingly to the Net C. The explanation to the observed results is two-fold – the harvest rate differences and the species composition of the managed growing stock. Recall, the request to increase the managed growing stock by the end of the planning horizon had negative impacts on the harvest rates, more visibly for the 20% increase managed growing stock scenario (Figure 1). These changes in the forest estate model translated accordingly in the C models – the C in forest declined over time, to a lesser degree for scenarios that retained more managed growing stock (Figure 15, top), and the C in HWP increased over time, to a higher degree for the scenarios that harvested more volume (Figure 15, bottom). Also recall, the C models stored more C in hardwoods than softwoods (Figure 9 and Figure 10). It follows, a higher proportion of softwoods should be stored in the managed growing stock, as illustrated in Figure 2 (e.g., in the case of V1_MMF_GS20, 11 million m^3 more softwood than base case, and only 6 million m^3 more hardwood).

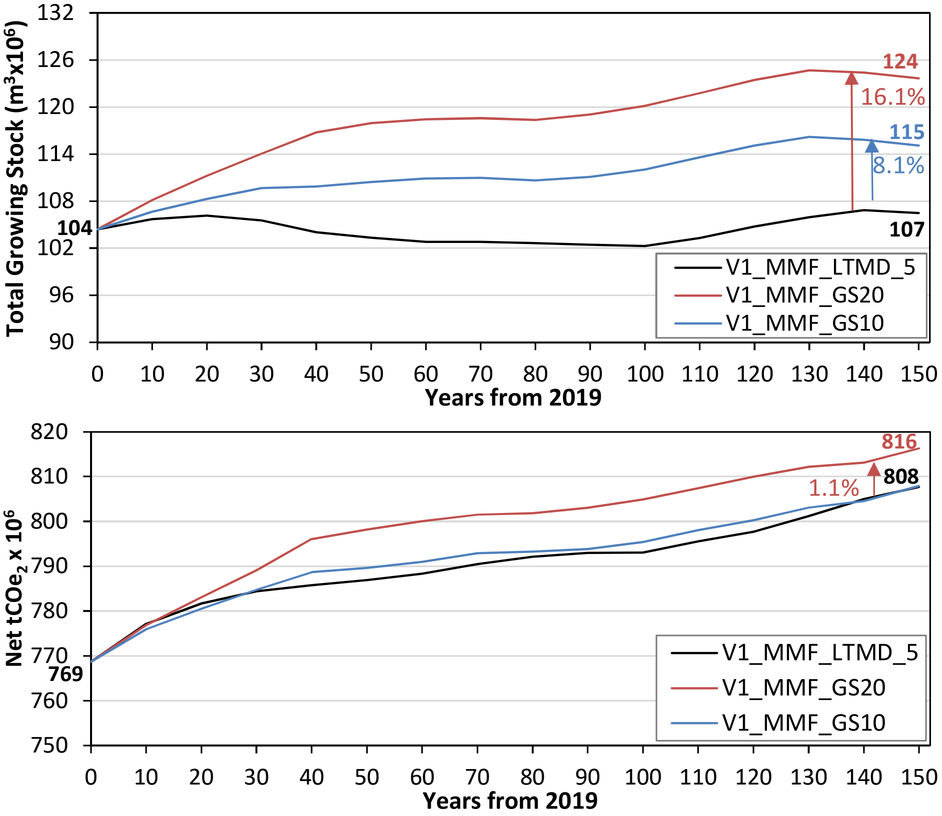


Figure 14 Comparing Total Growing Stock (top) and Net C Profile (bottom) for All Scenarios

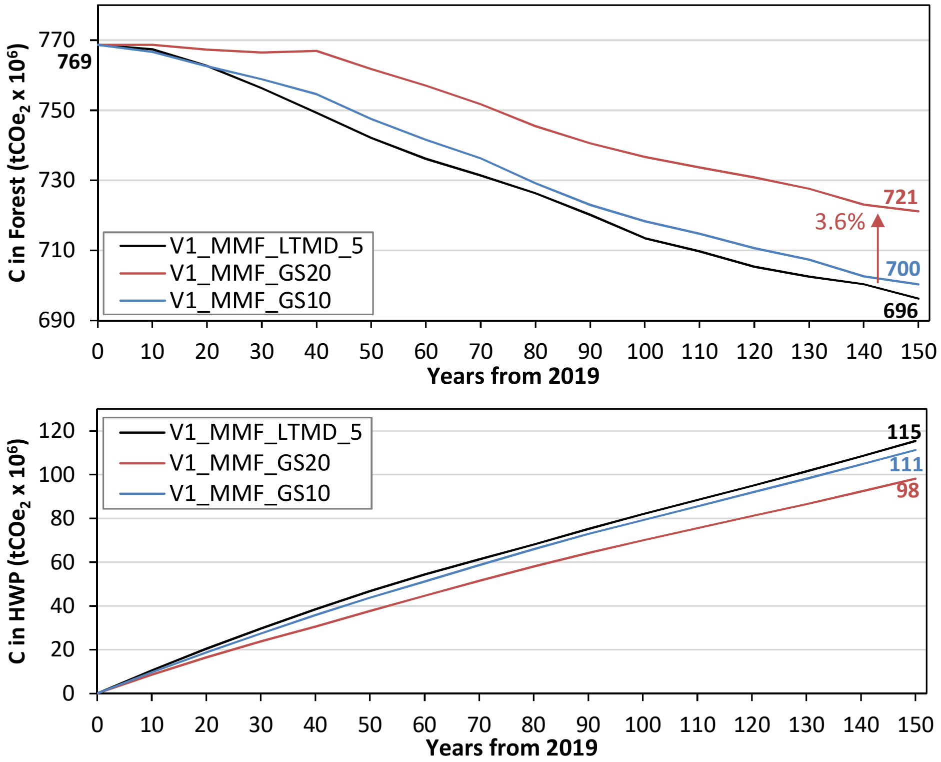


Figure 15 Comparing C in Forest (top) and HWP (bottom) for All Scenarios

A key finding was that for all scenarios, the growing stock (total or just managed) was steady or increasing over time (Figure 14 top), while the C in the forest decreased over time (Figure 15 top). In other words, the forest is being managed sustainably, but its carbon stores are dropping. This occurs because the average disturbance cycle in the managed forest is being converted to 60-120 years and more of the merch C is leaving the forest than when natural disturbances were occurring (i.e. moved into harvested wood products). Thus the DOM pool is falls over time until it reaches a new equilibrium for the disturbance type that is occurring (harvesting instead of fire). Figure 16 shows a case our dominate stand type where a harvest event was simulated every 80 years over a 500-year planning horizon. Here, the DOM (and total Ecosystem C) gradually declined in the first 4 cutting cycles before reaching a relatively steady-state between 2 consecutive cutting cycles.

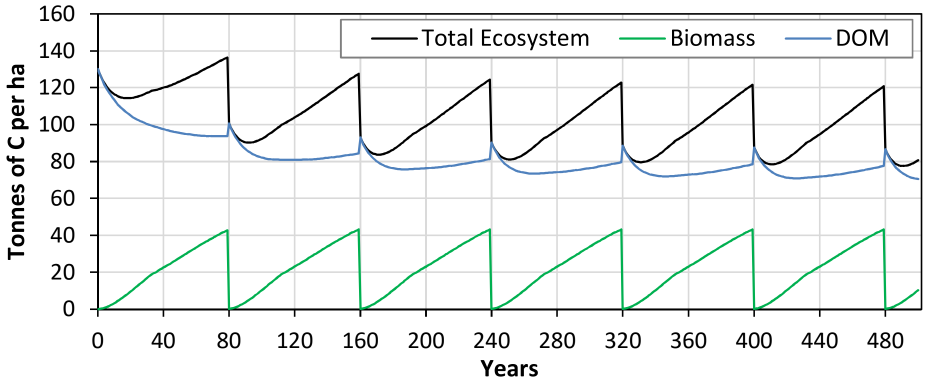


Figure 16 Example of C Stocks by Pools

3.3 NET INCREMENTAL DIFFERENCE

The net incremental change in carbon stocks illustrates the additional carbon stored or lost in a given time period relative to a baseline scenario – and it effectively represents the tonnes of CO2e that would be 'created' in a given period of a carbon offset project. Note – these tonnes would need to be discounted for issues such as risk of reversal and/or leakage, etc.

The net incremental difference (i.e., additional C stored) for the +10% GS scenario was only ~179,000 tCO2e more than the LTMD scenario over the 150 year planning horizon. The +20% GS scenario performed better and stored an additional ~8.63 million m^3 over the 150 years. Both scenarios showed considerable fluctuation over time (Figure 17 and Table 7).

It is noteworthy that the net incremental difference was not positive in all decades. Two factors contributed to these trends: the Net C slope changes between the scenarios, and the annual vs. multi-year projections. As illustrated in Eq. (2), the net-incremental difference is a function of the slope difference between two scenarios of interest. In the first decade, the LTMD scenario performed better, having an increasing steeper slope than the alternate scenarios. That reversed in the following 2-3 decades and additional C was stored. This cyclic trend continued for the remaining periods in the planning horizon. The factors that contributed to the slope changes were the C in forest, C in HWP, and the annual harvest schedule. While the declining C in forest was compensated for by the continual increase in HWP, a more subtle change occurred within each decade of the planning horizon, with an important impact on Net C. The harvest target in the forest estate model was placed at the decade level (e.g., 1 million m^3 per decade instead of 100,000 m^3/year). Consequently, the annual harvest rate varied substantially, generally with a relatively high harvest rate in the beginning of each decade and a relatively low (or zero) harvest rate towards the end of the decade. In theory, the forest estate model could have harvested the entire decade request in year 1 of the decade, and none for the rest of the decade. A higher harvest rate in the beginning of each decade gave the forest estate model a subtle “mathematical” advantage as the growing stock had recovered slightly more, the higher the initial annual harvest rate within the decade. Thus, the forest estate model harvested more in the beginning of each decade in the case of the GS10 and GS20 scenarios compared to the LTMD scenario, while the total harvest for each decade was higher for the LTMD. However, the annual harvest rate developed by the forest estate model is unrealistic. A workaround includes equally spread of harvest volume in each year of the decade, yet this approach diverges from the ideal situation where both, the forest estate model and the C budget model are perfectly aligned.

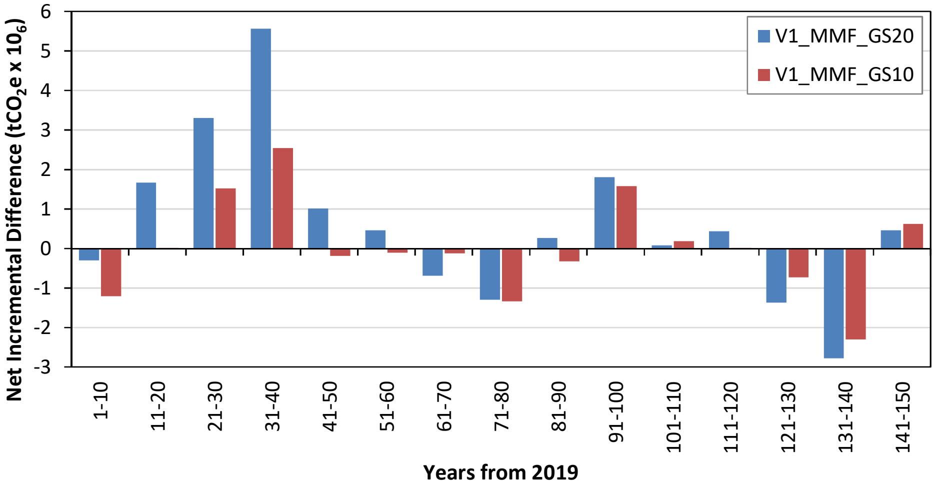


Figure 17 Additional C Stored at the End of Each Decade Compared to V1_MMF_LTMD_5 Scenario

Table 7 Additional C Stored at the End of Each Decade Compared to V1_MMF_LTMD_5 Scenario

Period (yrs)	V1_MMF_GS10 (tCO2e)	V1_MMF_GS20 (tCO2e)
1-10	-1,206,398	-298,796
11-20	13,924	1,672,085
21-30	1,523,333	3,307,047
31-40	2,545,753	5,567,293
41-50	-189,079	1,013,490
51-60	-105,078	461,007
61-70	-117,993	-684,384
71-80	-1,341,101	-1,298,016
81-90	-325,403	263,143
91-100	1,575,019	1,803,306
101-110	190,446	81,744
111-120	18,513	433,516
121-130	-729,885	-1,365,486
131-140	-2,295,532	-2,784,647
141-150	623,057	461,595
Total	**179,577**	**8,632,898**

The GS20 scenario would appear to offer the best option for a carbon offset project as it generates considerable C benefits in the first 4 decades (10.2 million t CO2e), and then produces a wide fluctuation of gains and losses after that point (period 5-15 total -1.6 million t CO2e). Thus a plausible scenario would look like selling ~5-8 million credits over the first 30-40 years (less insurance/leakage discounts) and then no further credits would be sold.

4 Conclusions

The results of this analysis suggest that the current LTMD for the MMF continues to store additional carbon over time when both forest and HWP C is considered (+5.1% by the end of the 150-year planning horizon). While the C storage within the forest ecosystem declines over time, the continuous accumulation of C stored in HWP is increasing over time and more than compensates for C losses within the forest ecosystem. C Losses in the forest ecosystem occur due to the difference in DOM storage that results from switching from natural (fire) disturbance regimes to forest harvesting disturbances. Less dead wood is created/held in the forest because more of it is being shifted to harvested wood products.

Additional C could be held in the forest ecosystem by asking the forest estate model to maintain more volume in the forest, or in modeling terms - increase the managed growing stock by up to 10% and 20%. The net incremental difference of these alternate scenarios, compared to the LTMD, indicated that by the end of the 150-year planning horizon, ~179,000 tCO_2e and ~8.63 million tCO_2e could potentially contribute to a carbon offset project when the managed growing stock is increased by up to 10% and 20%, respectively. By the end of year 10 of the 150-year planning horizon, none of the scenarios analyzed here resulted in positive C benefits compared to the LTMD but this is a modeling artifact that could be addressed in a more refined modeling exercise for a carbon offset project.

Given the C dynamics observed relative to species composition (softwood vs. hardwoods), future similar scenarios to store additional growing stock should consider a higher weight on hardwood growing stock than softwood. In addition, controlling harvest rates (i.e., a continuous harvest rate reduction over the entire planning horizon), or other more substantial changes to the forest estate model are expected to provide more C benefits.

While increased efforts were made to ensure an accurate alignment of the forest estate model and carbon budget models, uncertainties in regards to natural succession assumptions remained. Further research is needed to better align the management assumptions of natural succession used in typical timber supply and forest carbon budget analyses.

5 References

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