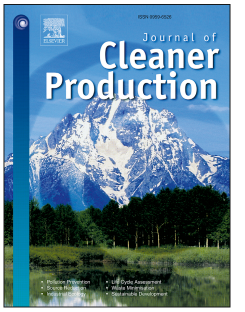
Accepted Manuscript



Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment

Marieke Head, Pierre Bernier, Annie Levasseur, Robert Beauregard, Manuele Margni

PII: S0959-6526(18)33832-0

DOI: https://doi.org/10.1016/j.jclepro.2018.12.122

Reference: JCLP 15180

To appear in: *Journal of Cleaner Production*

Received Date: 23 May 2018

Revised Date: 25 October 2018

Accepted Date: 12 December 2018

Please cite this article as: Head M, Bernier P, Levasseur A, Beauregard R, Margni M, Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment, *Journal of Cleaner Production* (2019), doi: https://doi.org/10.1016/j.jclepro.2018.12.122.

Title: Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment

Author names and affiliations:

Marieke Head : CIRAIG, Polytechnique Montréal, Mathematical and Industrial Engineering Department, C.P. 6079, succ. Centre-Ville, Montréal, QC, H3C 3A7, Canada

Pierre Bernier : Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du PEPS, CP 10380, Succursale Sainte-Foy, Québec G1V 4C7 Canada

Annie Levasseur : Département de génie de la construction, École de Technologie Supérieure, 1100 Notre-Dame West, Montreal, Quebec, Canada

Robert Beauregard : Faculté de Foresterie, de Géomatique et de Géographie, Université Laval, Québec, QC G1V 0A6, Canada

Manuele Margni : CIRAIG, Polytechnique Montréal, Mathematical and Industrial Engineering Department, C.P. 6079, succ. Centre-Ville, Montréal, QC, H3C 3A7, Canada

Corresponding author : Marieke Head, marieke.head@polymtl.ca, marieke.head@gmail.com

Word count: 9692

Forestry carbon budget models to improve biogenic carbon accounting in life cycle assessment

Marieke Head, Pierre Bernier, Annie Levasseur, Robert Beauregard, and Manuele Margni

Abstract

Currently, wood and wood construction materials have limitations in how carbon fluxes are accounted for in life cycle assessments. The biogenic carbon balance of wood is often considered to be neutral, meaning that the carbon sequestered by biomass through photosynthesis is considered equal to the carbon feedstock in wood that is eventually released throughout its life cycle. Several publications have recently shown that this assumption could lead to accounting errors. This research work aims to improve the biogenic carbon accounting of the forestry phase of the life cycle of softwood products. This involved specifically modelling carbon fluxes as a function of tree species, growing conditions and forest management practices, from Canadian managed forests. A baseline natural forest scenario was run for 1000 years until the carbon stocks were assumed to reach an approximate steady-state, followed immediately by a harvest scenario that was simulated for another 100 years. The ecosystem carbon costs of the harvest activity were calculated for 117 species and region forest landscapes across Canada and expressed per cubic meter of harvested wood. Most landscapes showed net sequestration after 100 years of harvest history. Exceptions to this included outlier landscapes characterized by low average annual temperatures and precipitation where slightly positive values (net emissions) were found. The mean time to ecosystem cost neutrality for each species ranged from 16-60 years. Knowing the time since forest management has started on a particular forest landscape now enables managers to obtain an estimate of ecosystem carbon cost per cubic meter of wood harvested for most of Canada's forests and commercial tree species. These ecosystem carbon costs can be used to generate regionalized cradle-to-gate life cycle inventories for harvested wood products across Canada.

Keywords: forestry, life cycle assessment, biogenic carbon, harvest, wood products

1. Introduction

Wood is commonly used as a building material throughout the North American construction sector. The life cycle assessment (LCA) methodology is increasingly used to assess and compare the potential environmental impacts of construction materials while considering all life cycle stages, from raw materials extraction to end-of-life (ISO, 2006a, b). However, the climate impacts of wood and wood construction materials currently have limitations in how they are accounted for in life cycle assessments. Since biomass is considered to be part of the fast domain of the carbon cycle, the carbon fluxes between the atmosphere and biomass have been differentiated from the carbon fluxes originating from fossil sources (Ciais et al., 2013). Being part of the fast domain of the carbon cycle, the carbon from biomass, known as biogenic carbon, is thus said to have a net carbon balance of zero, meaning that the carbon sequestered by biomass is equal to the carbon eventually released by that biomass. Several publications have shown that this assumption could lead to accounting errors (Garcia and Freire, 2014; Røyne et al., 2016; Searchinger et al., 2009; Vogtländer et al., 2013), incentives to clear-cut forests (Searchinger et al., 2009) or the creation of a temporal shift in carbon uptake and release causing an increase in cumulative radiative forcing (Helin et al., 2013). Moreover, this assumed net zero carbon balance has also been equated to a net zero climate change impact. Given the dynamic nature of biogenic carbon emissions and sequestration, the simplistic paradigm that carbon neutral equals climate neutral is also being questioned (Cherubini et al., 2011; Levasseur et al., 2012; Zanchi et al., 2010).

Net carbon neutrality is often argued based on the instantaneous oxidation approach used in early guidelines published by the Intergovernmental Panel on Climate Change (IPCC, 1997), whereby the carbon in harvested wood is considered emitted in the year of harvest. These guidelines also assumed that the net amount of carbon stored in harvested wood products was constant over time. However, the storage of carbon in harvested wood products is thought to be increasing as products are kept in use or are stored in landfills upon disposal (Lemprière et al., 2013). By using the instantaneous oxidation argument in Canada, where wood is used extensively in buildings, the greenhouse gas inventory emissions are overestimated (Dymond, 2012; Smyth et al., 2014). From a life cycle assessment perspective, considering a net carbon neutrality through all the life cycle stages of a wood product is an overly simplistic assumption on both the life cycle inventory and the potential impacts on climate change. In the forestry phase, a carbon neutrality approach ignores the site-specific carbon dynamics (Coursolle et al., 2012; McKechnie et al., 2011), and prevents that the carbon fluxes specific to forest ecosystems or forest management be factored into life cycle assessments. Within the use phase of a wood product, none of the temporary carbon storage or emission delays would be considered either (Brandão and Levasseur, 2011). Finally, at the end-of-life, the carbon neutrality approach can yield considerably different results compared to methods that quantify biogenic carbon of waste disposal options such as landfilling, recycling and incineration (Christensen et al., 2009; Levasseur et al., 2013; Muñoz and Schmidt, 2016).

Forests can act as either net carbon sinks or net carbon sources with respect to the atmosphere. Under normal growth conditions and in the absence of significant disturbances, forests are typically net carbon sinks as they absorb more carbon dioxide than they release to the atmosphere. When forests undergo stand-replacing disturbances such as fires or insect outbreaks, they usually become carbon sources as they release more carbon dioxide than they absorb from the atmosphere (Natural Resources Canada, 2016). Although most of the world's forests tend to be net carbon sinks (Pan et al., 2011), this source-sink interaction adds significant complexity to the forest carbon balance. From the perspective of life cycle assessment, the source-sink interactions of a managed forest need only to be benchmarked to a natural state in order to account for the human influence on harvested wood (Böttcher et al., 2008; Cao et al., 2016; Keith et al., 2009; Lessard, 2013).

Work on forest carbon dynamics has largely focused on the carbon balances for national greenhouse gas accounting (Kauppi et al., 2010; Kindermann et al., 2008; Kurz et al., 2009; Kurz et al., 2013; Luyssaert et al., 2007). Recently a few authors have considered the lack of consistent forestry carbon accounting in LCA. In a recent review of approaches, Helin et al. (2013) found large differences in how forest carbon stocks are considered in LCAs. Out of the 26 studies reviewed, eleven considered all aboveground and belowground carbon pools in modelled forestry carbon stocks, while in another cross-section nine studies (of the 26) used a IPCC Tier 3 approach (IPCC, 2006). Some authors proposed simplified approaches that can easily be applied to forest systems around the world. While these approaches are flexible and versatile, they may result in a high degree of uncertainty due to the variation in tree species, climatic conditions and forestry management practices possible in the world's forests. Only five studies (of the 26) were based on national forest inventory data, an approach which allows for tracking carbon exchanges over time through various forestry management scenarios. One of these last five is that of McKechnie et al. (2011) in which the authors present a framework to integrate life cycle inventory (LCI) and forest carbon modelling. They evaluated a regional-level forest-based bioenergy case in Ontario (Canada) using the FORCARB2 model. Although McKechnie et al. (2011) focused on a Canadian case study, they focused on one region within the province of Ontario and presented aggregated results for all tree species. While the FORCARB2 model makes use of robust empirical estimates of aboveground forest carbon pools, the model cannot simulate natural disturbances such as wildfires (Zald et al., 2016). Our work aims to improve on the cases presented above and to model forest carbon for several species and regions across Canada through the calculation of a natural forest state that includes wildfires.

The work we presented below is part of a larger research project on the use of wood as a building material within the context of Canadian forests. The extent and slow growth rates of Canadian forests and the prevalence of natural stand-replacing disturbances make these forests and forestry management different from that of other forestry regions. The frequent natural stand-replacing wildfires in these forests are an integral part of their natural dynamics (Boulanger et al., 2014; Stocks et al., 2002). In comparison to forests in other regions, the slow growth rate of boreal trees results in much lower biomass volume accumulation on a given area over time (Bogdanski, 2008; Brandt et al., 2013; Jarvis and Linder, 2000) and thus long intervals between successive harvests.

This research work aimed at improving biogenic carbon accounting in the life cycle assessment of softwood products by specifically modeling carbon fluxes of the forestry phase as a function of tree species, growing conditions and forest management practices. More specifically, the objective of this work was to quantify the net impact of harvest activities on the ecosystem carbon costs of forest ecosystems in Canada. This was achieved by calculating the carbon fluxes of harvested forests covering a range of climatic conditions and disturbance rates found across the Canadian managed forest, and for softwood tree species commonly used in Canadian building construction. The resulting carbon fluxes were then allocated to the units of wood harvested in a given landscape, allowing for the calculation of carbon fluxes of cradle-to-gate wood harvest in LCA.

2. Methods

2.1. Modeling forestry carbon fluxes for softwood harvest

From the perspective of a building planner choosing a building material, a wood product could be made from many different softwood tree species and could originate from any Canadian managed forest. As such, the scope of the forest carbon flux calculations covered the most common softwood tree species harvested commercially for building materials across Canada. This translated into the creation of several landscapes that are specific for a given species, Canadian province (or territory) and terrestrial ecozone. Each of these landscapes was subjected to disturbances, resulting in changes in the carbon stored and emitted from that forest that are specific to each landscape.

The terms used in this text to refer to carbon dynamics are defined below:

Biomass: Biomass is the mass of all living vegetation which includes both aboveground (stem, stump, branches, bark, seeds and foliage) and belowground (roots) portions of trees. In the context of this paper, dead trees (snags) and non-tree biomass (moss, shrubs) are excluded.

Total carbon stocks (TCS): Refers to the sum of carbon mass across all ecosystem carbon pools (in tC·ha^{-1}) in a given area of forest, including all biomass and dead organic matter (DOM) (including soil).

Net carbon flux (NCF): The net result of the uptake of carbon through photosynthesis and carbon losses through plant respiration or decomposition. At the forest landscape level, *NCF* includes carbon losses due to fire as well as the removal of carbon through the harvesting of wood. In this study, positive values of *NFC* represent a net forest C loss to the atmosphere.

Ecosystem carbon cost (ECC): Within the context of this study, the net carbon flux of the forest to the atmosphere attributed to the harvesting activity. *ECC* is calculated at the landscape level and expressed per unit of wood (cubic meters or tonnes) harvested per year. Positive values of *ECC* represent net forest C losses to the atmosphere.

Time to ecosystem cost neutrality: The number of simulated harvest years required for the *ECC* to cross the zero line and reach carbon neutrality.

Sequestration: A net carbon flux between the atmosphere and the forest that results in increased *TCS* over one or more years. In the context of this paper, the forest is considered from a landscape-level meaning that it also includes the effect of fire. Sequestered C can be transferred out of the forest and remain sequestered as wood products.

The modelling of forest ecosystem carbon dynamics was carried out using the CBM-CFS3 software (Kurz et al. 2009). CBM-CFS3 is a carbon budget model developed by the Canadian Forest Service (Natural Resources Canada) that keeps track of carbon fluxes within user-defined forest landscapes, as driven by tree growth, natural disturbances and forest management (Figure 1). The CBM-CFS3 can be used to simulate forest carbon dynamics in forests of any composition across Canada, but does not account for non-tree plant species in its calculations. The model can be used at the level of stands and of landscapes, which allows for the landscape-level approach suitable to this research (Zald et al., 2016). A landscape-level perspective considers a much larger forest area than the stand-level perspective and consists of stands of differing ages, disturbance histories, species compositions and site conditions, across which disturbances take place. The CBM-CFS3 model can simulate natural disturbances (Zald et al., 2016), which allows for the estimation of a natural baseline state in the forest, as well as of transient states where forest management is a recent addition to the landscape dynamics.

The three main inputs to the model were areas per tree species and age class, volume over age (yield) curves and area affected annually by disturbance type (Figure 1). The model provides annual estimates of C stocks by ecosystem reservoir, the sum of which give annual values of *TCS*. We calculated annual values of *ECC* as the interannual difference in *TCS* of the forest landscapes, minus the carbon contained in the harvested wood. The resulting values were expressed in $tC{\cdot}ha^{-1}{\cdot}yr^{-1}$ as well as in $tC{\cdot}m^{-3}$ of harvested wood yr^{-1} or $tC{\cdot}t^{-1}$ harvested wood, using the LCA sign convention of representing a flux to the atmosphere as a positive value. More details on these calculations can be found in section 2.5.

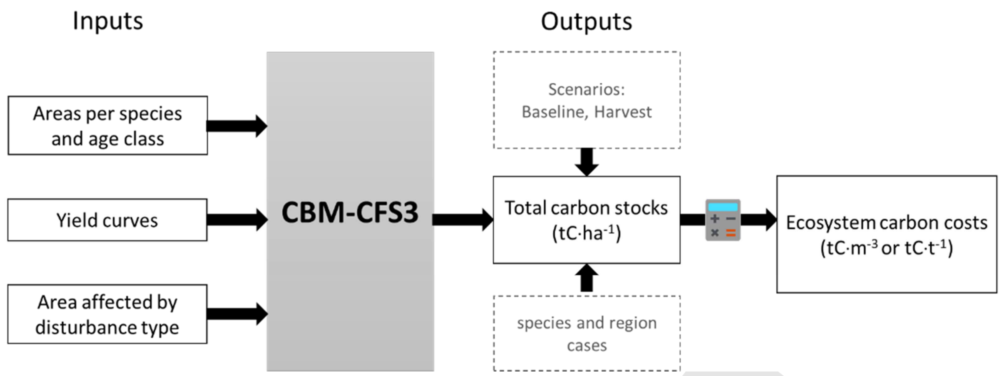


Figure 1 – Schematic overview of inputs and outputs used with CBM-CFS3

Vectorial maps of commercial softwood tree species distribution across Canada were created using the 250-m resolution Canada-wide maps of tree composition from Beaudoin et al. (2014). The boundaries of the tree species maps were set by drawing vector polygons of the pixel clusters representing the forested areas. These maps were then overlaid with a map of the Canadian managed forest area, of provincial and territorial boundaries and of ecozones (Ecological Stratification Working Group, 1996). The intersections of 14 softwood tree species, 12 Canadian provinces and territories, and 13 terrestrial ecozones yielded 266 landscapes that range in area from 30 to 4 800 000 ha.

The age frequency distribution for each species and terrestrial ecozone were calculated using the 250m-resolution stand age and forest composition maps of Beaudoin et al (2014) taken in 2001 as a frequency distribution of pixel counts per 10-year age increment. The surface area of each age class in each landscape was calculated as the product of age frequency per 10-year age increment and the total surface area of each landscape. These age distributions were used as a starting point for the simulations.

2.2. Yield curves

A yield curve is an empirical relationship that predicts the wood volume of a stand of a given tree species as a function of the stand age. Such curves are required inputs for the CBM-CFS3 model. For our analysis, we used the national yield curves of Ung et al. (2009) that had been parametrized for most commercial tree species in Canada using data obtained in field plots across the country:

Eq. 1 $\ln V = v10 + v11T + v12P + ((v20 + v21T + v22P) / A)$

Eq. 2 $V = \ln(V)Cd$

Where,

V = Gross total volume of live merchantable trees ($m^3 \cdot ha^{-1}$); a merchantable tree has a diameter at breast height (dbh) greater than 9 cm
vij= species-specific coefficients for 25 species
T = mean annual temperature (°C)
P = total precipitation (mm)
A = Plot age (yr)
Cd = correction factor

We calculated the values of mean annual temperature (T) and total precipitation (P) for each of the defined landscapes using 1981-2010 climate normal maps (McKenney et al., 2016). The resulting values were used as inputs in equations 1 and 2, with A ranging from 0 to the maximum natural lifespan (Burns and Honkala, 1990) of each species. Considering the mathematical basis of the yield curve model and the calculated coefficients, landscapes with atypical yield curves were discarded (23 cases) yielding a new total of 243 landscapes to be simulated.

2.3. Area affected by disturbance type

The disturbances defined in the CBM-CFS3 simulations in the model are fire and harvest, hence only those disturbances were considered in our analysis. Values of mean percent annual area burned within each ecozone were first calculated as the area-weighted mean of the homogeneous fire regime zones defined by Boulanger et al. (2014). For each of our 243 landscapes, we then calculated a value of mean annual area burned as the product of its ecozone annual burn rate and the area of the landscape. Values of mean annual area harvested were calculated using published historical area-based harvest rates by forest management units across Canada (Gauthier et al., 2015). Based on the proportional area of each unit, a weighted mean of harvest intensity was calculated by ecozone. These harvest intensities were then multiplied by the areas of each landscape to obtain mean annual harvested area by landscape. The complete list of the harvest rates and climatic data can be found in the Supplementary Material (Table A.2).

2.4. Creation of simulation scenarios

Two management scenarios were developed for this study:

- The *baseline scenario* simulates the carbon fluxes between the forests and the atmosphere under natural no-harvest conditions, where a proportion of each landscape is subjected to a constant annual burn rate for a 1000-year period (Boulanger et al., 2014). For the purpose of this work, the forest is assumed to have reached an approximate steady-state at 1000 years.
- The *harvest scenario* includes both the regular natural disturbance regimes of the baseline scenario as well as an annual harvest based on the regional harvest rates reported in Gauthier et al. (2015), and continues from the steady-state point of the baseline scenario for a simulation period of 100 years (thus from year 1001-1100) adding forestry harvesting activities. As shown by McKechnie et al. (2011), a 100-year period is consistent with long-term forestry management. It also reflects the historical period of management across most of Canada's forests. The harvest scenario does not include the collection of harvest residues.

2.5. Calculation of carbon fluxes

CBM-CFS3 simulations were initialized across all 243 species and region landscapes at year 0 using forest composition and age class distribution for the year 2001 from Beaudoin et al. (2014), region- and species-specific yield models from equations 1 and 2, and disturbances based on Boulanger et al. (2014) and Gauthier et al. (2015) as described above. For a given landscape, for each year, the model calculated the mean value of carbon stocks per hectare as well as the mean value of carbon in the harvested wood, also expressed per hectare.

As mentioned above, the baseline scenario at year 1000 was taken as an approximate steady-state reference point for each of the landscapes, which was followed directly by the harvest scenario for 100 years (thus from year 1001 to year 1100). The ecosystem carbon costs *($ECC_{harvest}$)* of harvest in the forest ecosystem were calculated as the annual intervals or the partial derivatives of the *total carbon stocks* (TCS), subtracted by the carbon contained in the wood harvested annually, for each harvest simulation year or $0 \leq t \leq 100$ years:

Eq. 3 $ECC_{harvest,\, t}$ (tC/(ha yr)) = $\partial/\partial t$ TCS - C content of wood harvested

To convert ECC results from $tC{\cdot}ha^{-1}{\cdot}yr^{-1}$ to $tC{\cdot}m^{-3}$ wood and $tC{\cdot}t^{-1}$ wood, the amount of wood harvested each year in a given landscape was first converted to m^3 $wood{\cdot}ha^{-1}{\cdot}yr^{-1}$ and t^{-1} $wood{\cdot}ha^{-1}{\cdot}yr^{-1}$.:

Eq. 4a Wood harvested (m^3wood/(ha yr)) = C content of wood harvested (tC/(ha yr)) / ((0.5tC/twood) x (wood density$_{species}$ (twood/m^3wood)))

Eq. 4b Wood harvested (twood/(ha yr)) = C content of wood harvested (tC/(ha yr)) / (0.5tC/twood)

The ecosystem carbon costs for the harvest scenario over a landscape was then converted to ecosystem carbon costs per volume of wood harvested, such to allocate the carbon fluxes to the amount of wood harvested instead to the managed forest surface:

Eq. 5a ECC (tC/m^3wood) = ECC$_{harvest}$ (tC/(ha yr)) / wood harvested (m^3wood(ha yr))

Certain results were also calculated per mass of wood harvested in order to assess the proportion of carbon content that ecosystem carbon costs represent:

Eq. 5b ECC (tC/twood) = ECC$_{harvest}$ (tC/(ha yr)) / wood harvested (twood/(ha yr))

The ecosystem carbon costs, as calculated by equation 5a, were plotted for all 243 landscapes. We then examined all curves and eliminated from the analysis landscapes in which carbon stocks still increased during the period with harvest or followed an erratic trajectory, as well as landscapes whose combination of species and geographic range was deemed to be commercially irrelevant to the Canadian wood industry. The remaining 117 landscapes, listed in Table A.3 of the Supplementary Material. were used for the analysis.

2.6. Aggregated results over larger regions

In addition to providing detailed results for specific species and regions, we also calculated aggregated results to account for the perspective of a wood user who might not know the species or regional origin of a given wood product. The aggregation is based upon the calculation of the weighted mean of all landscapes, where the weights are based on harvest volumes of species by regions across Canada (National Forest Inventory, 2013). Weighted means were calculated for each species, each province as well as for Eastern and Western Canada wood markets.

2.7. Evaluation against monitored data from flux towers

Carbon flux results obtained using the CBM-CFS3 simulations were validated against empirical CO_2 flux measurement data. For several years, the Canadian Carbon Network measured CO_2 exchanges across a network of forest sites in Canada using eddy covariance flux towers (Coursolle et al., 2006; Margolis et al., 2006). One of the sites near Chibougamau, Quebec, is covered by a mature forest dominated by black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) (Bergeron et al., 2007; Bernier and Paré, 2013; Bernier et al., 2010; Margolis et al., 2006). The history of the site includes wildfire between 1885 and 1915 affecting 74% of the site and harvest in the 1960s affecting 17% of the site area (Margolis et al., 2016). Carbon flux measurements from this flux tower have been already been used in many analysis, including a comparison of ecosystem carbon models (Bernier et al., 2010), and the calculation of carbon debt from bioenergy use (Bernier and Paré, 2013).

The flux tower on-site gathered high-frequency measurements of vertical wind velocity, air temperature, water vapour density and CO_2 concentrations in the air, which were then transformed into estimates of CO_2 fluxes as NEE (net ecosystem exchange) for half-hour intervals from 2003 to 2010 in terms of $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$ (Coursolle et al., 2006). We averaged for each year the half-hourly NEE values for every year from 2004 to 2010 (measurements for 2003 only covered from June to December). To obtain a carbon flux in $tC \cdot ha^{-1} \cdot yr^{-1}$, the annual averages were multiplied by the ratio of the molar mass of CO_2 over the molar mass of C. An average over the period 2004-2010 was calculated such as to smooth out the interannual variability of the flux tower data and used it as a benchmark to evaluate model results.

These values were plotted alongside modelled ecosystem carbon costs of black spruce and jack pine landscapes within the Quebec Boreal Shield, for the baseline scenario as well as the harvest scenario. Although the modelled landscapes describe an annual disturbance and flux tower stands have been subject to infrequent disturbances, an attempt was made to manage the inherent differences between these two datasets. This was done by offsetting the simulation period of the modelled landscape curves to correspond with the number of years since the disturbance events of the flux tower stands. For example, wildfire affected the stands surrounding the flux tower at year 0, which was used as the start year for the modelled post-fire baseline landscape, and a wildfire scenario was run for 118 years to estimate carbon stocks at year 118. Similarly, harvest occurred at year 65 and thus the harvest scenario was run for a further 100 years (year 65-year 165) as to estimate carbon stocks at year 118.

3. Results and Discussion

The data points in the figures presented in this section can be found in the Supplementary Material.

3.1. Total carbon stocks

The baseline scenario reached an approximate steady-state in total carbon stocks after a landscape-level spin up period of 1000 years, following an initial spin-up designed to reach an initial equilibrium among carbon pools at the site-level (Figure 2). The spin-up refers to an initialization step executed by the CBM-CFS3 that assigns values to the dead organic matter (DOM) pool which is not measured as part of the regular forest inventory. A constant harvest regime from years 1001 to 1100 was imposed on the land-scapes following the realization of the baseline steady-state. The carbon stock values on the harvest curves were used as inputs to the calculation of ecosystem carbon cost for each cubic meter of harvest-ed wood (Eq. 3).

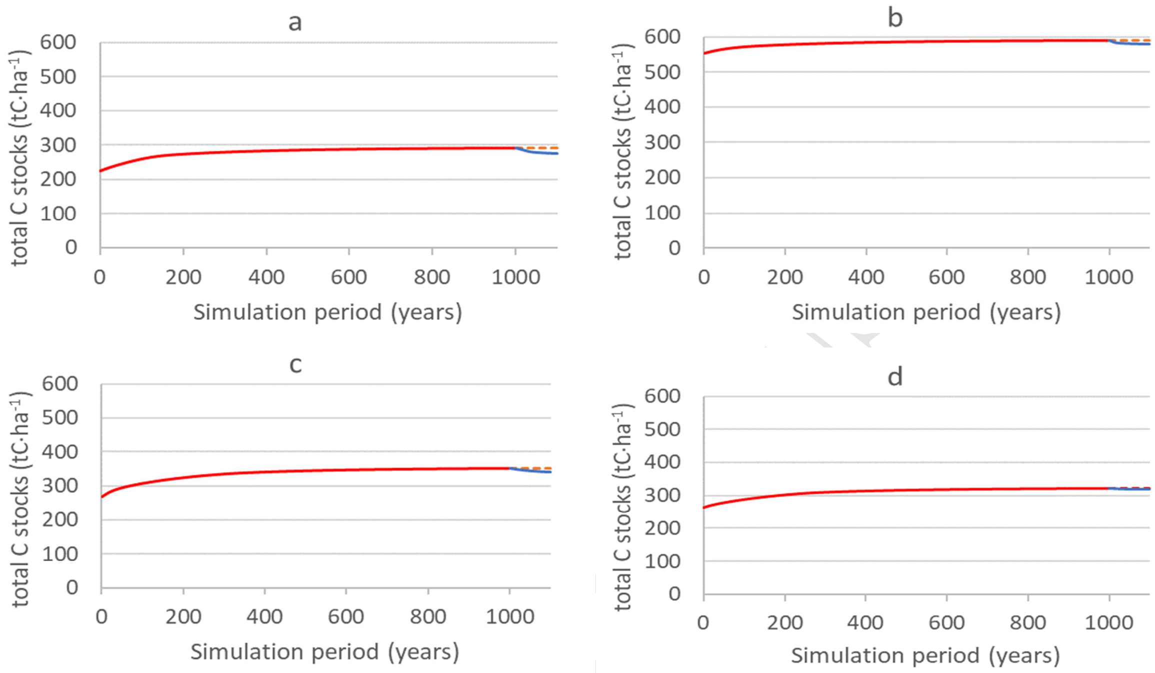


Figure 2 – Total carbon stocks of the baseline period from 0-1000 years (red line), followed by a harvest period from 1001-1100 years (blue). The dotted red lined represents the approximate steady-state value of the baseline period at 1000 years. a) Balsam fir (Abies balsamea), Quebec, Boreal Shield East, b) Lodgepole pine (Pinus contorta, British Columbia, Pacific Maritime, c) Western larch (Larix occidentalis), Alberta, Subhumid Prairies, d) White spruce (Picea glauca), New Brunswick, Atlantic Maritime.

The baseline curve shows a rapid increase in total carbon stocks in the first few hundred years, followed by a flattening out as the forest carbon approaches a steady-state, as younger trees are re-established in the landscapes (Figure 2). The total carbon stocks of the harvest regime decreased from the baseline steady-state as expected and similarly to the results of Lessard (2013) for a landscape modelled in the Quebec Boreal Shield. This sample of four landscapes in Figure 2 also shows that the total carbon stock curves for the harvest regime vary by species type and ecozone, as a result of differences in the growth rates of the trees and the proportion of biomass affected by disturbances.

3.2. Ecosystem carbon costs of harvest activity

Using the total carbon stocks of just the harvest period (from 1001-1100 years) as well as the carbon content of the wood harvested annually per hectare, the ecosystem carbon costs were calculated using eq. 5 for all the landscapes. The ecosystem carbon costs curves are shown for four landscapes (Figure 3).

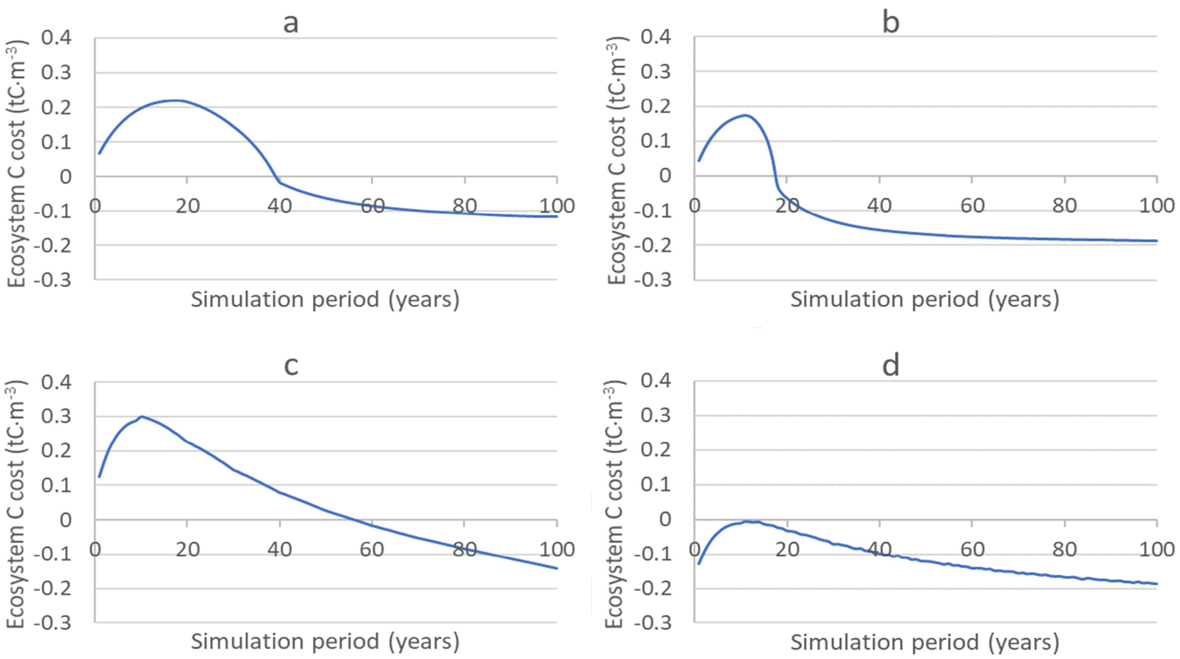


Figure 3 – Ecosystem carbon cost, as net annual loss of carbon from the forest ecosystem to the atmosphere per cubic meter of wood harvested that year (tC·m^{-3} wood) for four sample landscapes, as calculated with eq. 5a. The 0-100 period corresponds to the 1000-1100 period in Figure 2. a) Balsam fir (Abies balsamea), Quebec, Boreal Shield East; b) Lodgepole pine (Pinus contorta), British Columbia, Pacific Maritime; c) Western larch (Larix occidentalis), Alberta, Montane Cordillera; d) White spruce (Picea glauca), New Brunswick, Atlantic Maritime. Positive values represent a net C loss to the atmosphere, while negative values represent a net C gain from the atmosphere.

While the calculations of total carbon stocks (Figure 2) include the transfer of carbon to harvested wood, here, those of *ECC* represent only the net loss in carbon to the atmosphere and are further expressed per unit of wood harvested (Figure 3 and Eq. 3). For all four sample landscapes (a-d), the *ECC* increases rapidly in the first decade and are followed by a decrease.

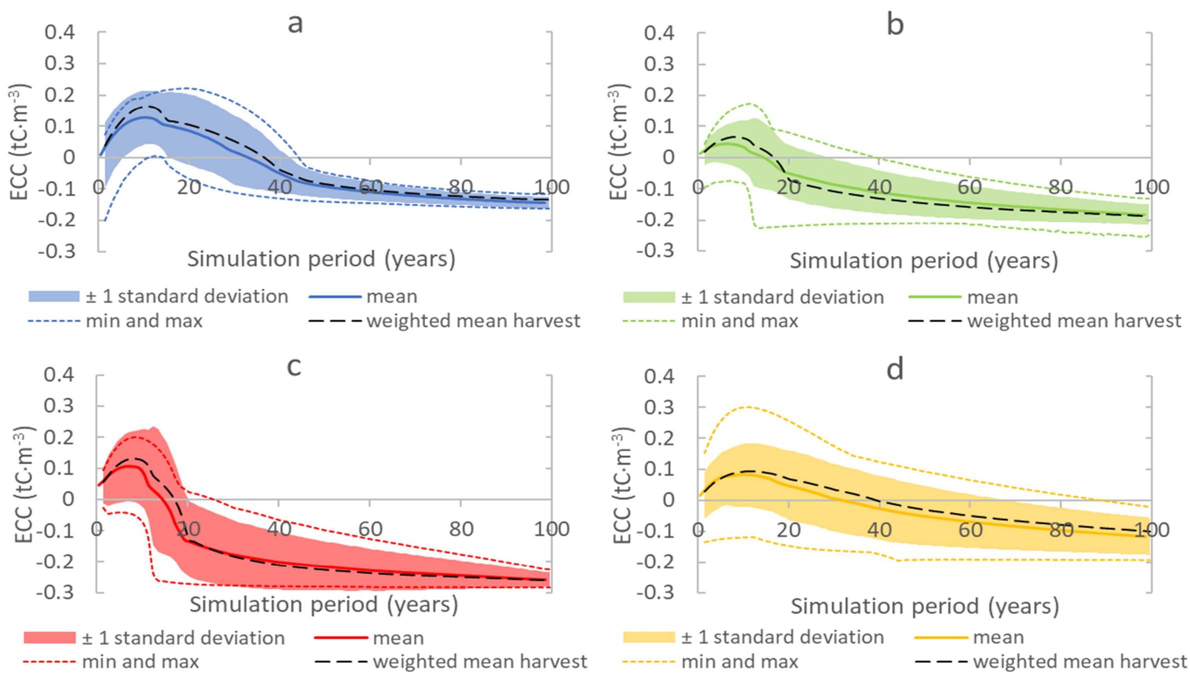


Figure 4 – Ecosystem carbon cost (ECC) by cubic metre of wood harvested for four common softwood tree species across Canada. The curves represent the interannual intervals of the harvest activity minus the carbon contained in the harvested wood, divided by the carbon content of the annual harvest volume (see eq. 5a). a) Balsam fir (Abies balsamea), all occurrences, b) Lodgepole pine (Pinus contorta), all occurrences, c) Western larch (Larix occidentalis), all occurrences, d) White spruce (Picea glauca), all occurrences. The dark centre lines show the mean species and regions, the lighter bands ±1 standard deviation, the dotted lines the minimum and maximum and the black dotted lines are the weighted average based on harvest volumes.

While Figure 3 illustrated the curves for four individual landscapes, the curves in Figure 4 show the statistical spread of the landscapes for each species, which includes the landscapes featured in Figure 3. As with the individual landscapes (Figure 3), the statistical spread curves (Figure 4) show increased values of *ecosystem carbon cost* over the first few years of simulation, followed by a decrease over the 100-year simulation period. After a few decades, the curves cross the zero line as the landscape becomes a net carbon sink. This *time to ecosystem cost neutrality* varies between landscapes, with the mean for each species ranging from 16-60 years. At the two extremes, are a small number of landscapes that have either curves entirely with negative ecosystem carbon cost values or curves with positive ecosystem carbon costs that never reach carbon neutrality. The variability in time to ecosystem cost neutrality is affected by the shape and amplitude of the curves. The shapes of the curves are determined by the species-specific coefficients used in the yield curve equations (see equations 1 and 2), while the amplitude of the curves is related to the harvest rates and the climatic data used for creating the yield curves. The shape of the balsam fir and white spruce curves are similar, as the ecosystem carbon costs decrease steadily over time, while the lodgepole pine and western larch curves exhibit much steeper and rapid decreases.

Higher temperatures and precipitation tend to result in more biomass accumulation per year per hectare of forest and thus these landscapes have increased carbon sequestration capacity. This increase in carbon sequestration capacity means that landscapes are less affected by disturbances and thus have lower forest-to-atmosphere carbon fluxes. For example, in the case of balsam fir, the highest ecosystem carbon costs are associated with relatively low temperatures and precipitation (1.0-2.2°C and 800-1000 mm), while the lowest fluxes were found where temperature and precipitation were highest (6.4-6.9°C and 900-1400 mm). The complete list of the harvest rates and climatic data can be found in the Supplementary Material (Table A.2).

The weighted Canada-wide mean ecosystem carbon costs based on production volumes for each species across simulation years are close to the calculated mean curves (Figure 5a and 5b).

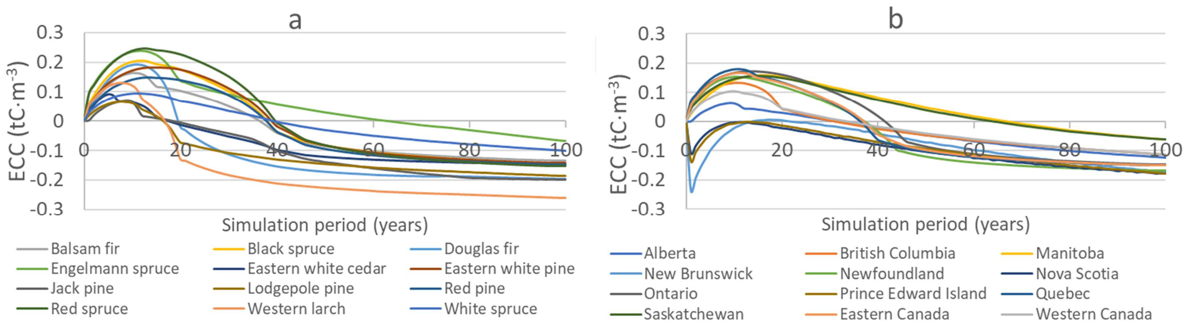


Figure 5 – Weighted mean of ecosystem carbon costs of harvest activity, by a) tree species b) provinces. Weights are harvested volumes.

The ecosystem carbon cost curve of each landscape is affected by the species-specific coefficients used in the yield curve equations, as well as regionally-specific climatic data and annual harvest rate, yielding significant differences among the weighted averages by species and by region. By species (see Figure 5a), the ecosystem carbon costs per m^3 of wood are highest for the spruce species (Engelmann spruce, white spruce, black spruce and red spruce), and lowest for certain pine species (lodgepole pine and jack pine) as well as western larch and eastern white cedar. When calculated by region (Figure 5b), the ecosystem carbon costs are highest for the western Canada provinces (Manitoba, Saskatchewan, Alberta and British Columbia) and lowest for Atlantic Canada (Prince Edward Island, Nova Scotia, New Brunswick and Newfoundland).

After 100 years of simulated harvest activity, the ecosystem carbon cost per m^3 (or tonne) of harvested wood is negative (net sequestration) for almost all landscapes (Figure 6). When the results are presented by species (Figure 6a and b), the median values range from -0.26 to -0.098 $tC{\cdot}m^{-3}$ (-0.48 to -0.27 $tC{\cdot}t^{-1}$), whereas the boxes range from -0.27 to -0.032 $tC{\cdot}m^{-3}$ (-0.50 to -0.090 $tC{\cdot}t^{-1}$) and outliers range from -0.28 to 0.15 $tC{\cdot}m^{-3}$ (-0.73 to 0.043 $tC{\cdot}t^{-1}$). The weighted mean based on harvest volumes ranged from -0.26 to -0.069 $tC{\cdot}m^{-3}$ (-0.48 to -0.19 $tC{\cdot}t^{-1}$). The species with the highest ecosystem carbon costs are spruce (such as white spruce, black spruce, Engelmann spruce), due to both higher rates of harvest in combination with lower temperatures and precipitation in the growing regions. In addition, the spruce species show more variation across regions than other species. For white spruce, this could be caused by the larger number of landscapes (24), whereas the larger variation within black spruce and Engelmann spruce could be as a result of large geographical range of those species. In other cases, such as jack pine (18 landscapes) which is harvested across Canada, the species are less sensitive to variations in temperature and precipitation. The interquartile ranges of the remaining species are clustered together. Despite these few trends, the spread of data shows that the region of origin of the species could be important information for pinpointing a more precise ecosystem carbon cost.

When the results are presented by region, the statistical spread of the data shifts somewhat (Figure 6c and d). The median values per province range from -0.22 to -0.059 $tC{\cdot}m^{-3}$ (-0.55 to -0.15 $tC{\cdot}t^{-1}$), whereas the boxes range from -0.24 to -0.030 $tC{\cdot}m^{-3}$ (-0.66 to -0.083 $tC{\cdot}t^{-1}$) and outliers range from -0.28 to 0.015 $tC{\cdot}m^{-3}$ (-0.73 to 0.043 $tC{\cdot}t^{-1}$). The weighted mean based on harvest volumes ranged from -0.18 to -0.034 $tC{\cdot}m^{-3}$ (-0.50 to -0.085 $tC{\cdot}t^{-1}$). For two Atlantic Canada provinces (New Brunswick and Nova Scotia), most of the interquartile range (representing the middle 50% of values) showed more net sequestration than any of the other provinces. This is related to both very low levels of harvest in the New Brunswick and Nova Scotia landscapes with their higher mean annual temperatures and precipitation levels, are characteristic of coastal forests and show the most negative values of ECC at 100 years illustrating the strong carbon sink per unit of harvested wood. On the other end of the spectrum, Manitoba and Saskatchewan landscapes with their low mean annual temperatures and precipitation show either less sequestration (small negative values) or slightly net emissions (small positive values) per unit of wood harvested. All data points shown in Figure 6 are available in table form in the Supplementary Material (Table A.4).

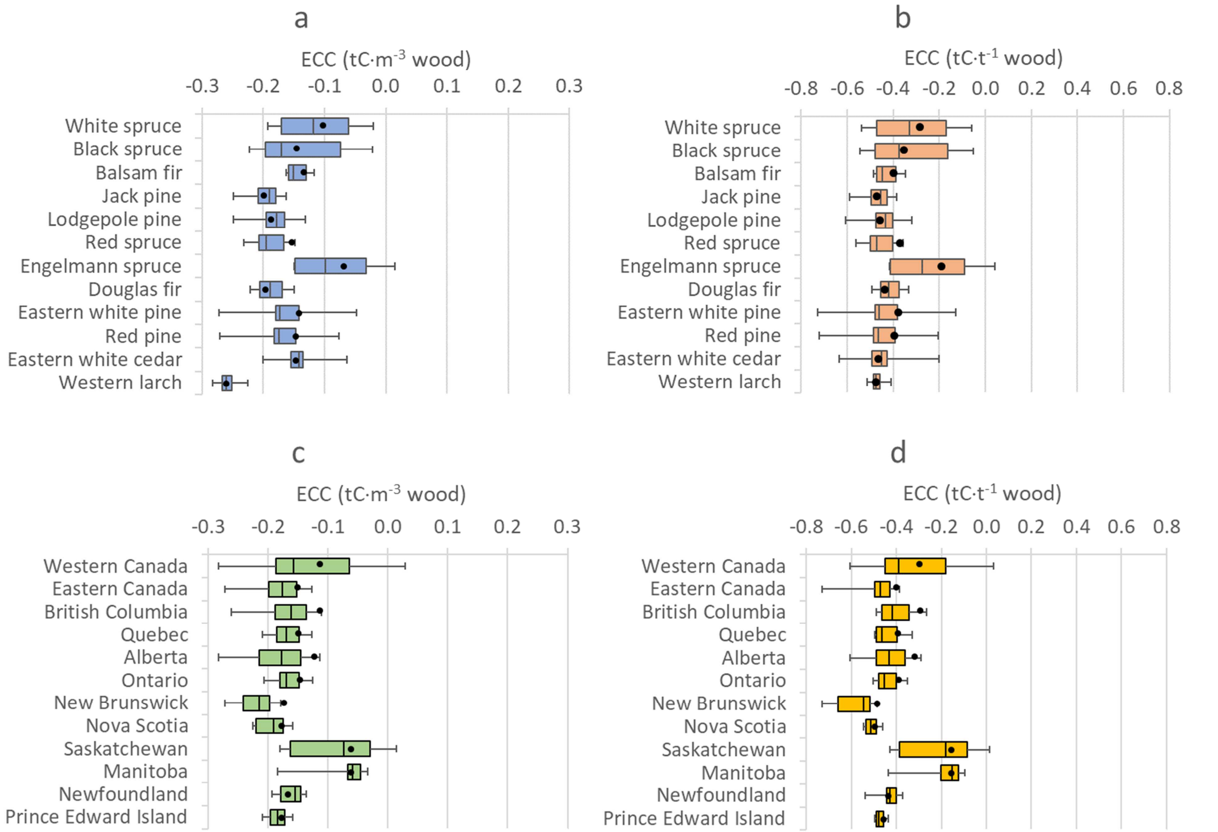


Figure 6 – Ecosystem carbon costs at year 100 of simulation, for a) per tree species in tC·m^{-3} wood harvested, b) per tree species in tC·t^{-1} wood harvested, c) per region in tC·m^{-3} wood harvested, d) per region in tC·t^{-1} wood harvested. The carbon content of the dry wood ranges from 0.175 tC·m^{-3} wood harvested (Eastern white cedar) to 0.300 tC·m^{-3} wood harvested (Western larch). The lower and upper error bars show the minimum and maximum values, while the lower bound of the box shows first quartile value, the middle line the median value and the upper bound the third quartile value. The round markers indicate the weighted mean values according to approximate annual wood harvest volumes.

Table 1 – Ecosystem carbon costs at year 100 of simulation, in tC·m^{-3} wood harvested

	mean	std dev	wgt mean by harvest volume	minimum	Q1	median	Q3	maximum	C in wood
Western larch (Larix occidentalis)	-0.257	0.024	-0.261	-0.283	-0.267	-0.261	-0.251	-0.225	0.300
Eastern white cedar (Thuja occidentalis)	-0.141	0.038	-0.147	-0.200	-0.155	-0.142	-0.135	-0.064	0.175
Red pine (Pinus resinosa)	-0.171	0.052	-0.148	-0.271	-0.183	-0.175	-0.147	-0.076	0.201
Eastern white pine (Pinus strobus)	-0.162	0.059	-0.141	-0.272	-0.179	-0.173	-0.142	-0.047	0.200
Douglas fir (Pseudotsuga menziesii)	-0.187	0.036	-0.197	-0.222	-0.205	-0.189	-0.169	-0.150	0.244
Engelmann spruce (Picea engelmannii)	-0.083	0.081	-0.069	-0.149	-0.149	-0.098	-0.032	0.015	0.195
Red spruce (Picea rubens)	-0.191	0.029	-0.154	-0.232	-0.207	-0.195	-0.167	-0.148	0.218
Lodgepole pine (Pinus contorta)	-0.182	0.032	-0.187	-0.249	-0.195	-0.178	-0.165	-0.131	0.215
Jack pine (Pinus banksiana)	-0.194	0.023	-0.199	-0.249	-0.208	-0.191	-0.180	-0.162	0.222
Balsam fir (Abies balsamea)	-0.144	0.020	-0.134	-0.163	-0.158	-0.150	-0.130	-0.117	0.175
Black spruce (Picea mariana)	-0.138	0.074	-0.130	-0.223	-0.197	-0.171	-0.074	-0.022	0.220
White spruce (Picea glauca)	-0.116	0.060	-0.104	-0.193	-0.171	-0.118	-0.061	-0.021	0.195
Prince Edward Island	-0.184	0.021	-0.046	-0.209	-0.197	-0.184	-0.172	-0.160	
Newfoundland	-0.162	0.022	-0.166	-0.193	-0.179	-0.154	-0.145	-0.135	
Manitoba	-0.072	0.044	-0.049	-0.184	-0.067	-0.059	-0.046	-0.041	
Saskatchewan	-0.095	0.063	-0.034	-0.180	-0.162	-0.074	-0.030	-0.021	
Nova Scotia	-0.193	0.028	-0.178	-0.225	-0.220	-0.191	-0.175	-0.155	
New Brunswick	-0.218	0.041	-0.174	-0.272	-0.242	-0.215	-0.197	-0.150	
Ontario	-0.166	0.026	-0.108	-0.207	-0.181	-0.169	-0.148	-0.117	
Alberta	-0.173	0.061	-0.068	-0.283	-0.215	-0.178	-0.146	-0.048	
Quebec	-0.165	0.030	-0.114	-0.210	-0.185	-0.169	-0.148	-0.081	
British Columbia	-0.151	0.072	-0.051	-0.262	-0.189	-0.162	-0.137	0.015	
Eastern Canada	-0.176	0.034	-0.115	-0.272	-0.199	-0.176	-0.152	-0.081	
Western Canada	-0.138	0.074	-0.055	-0.283	-0.187	-0.157	-0.064	0.015	

Forestry management is relatively recent in Canada, as compared to Fenno-Scandinavia, where forests have been extensively exploited for centuries (Kurz et al., 2013). However, some regions across Canada, such as the Maritime provinces, Eastern Ontario and Western Quebec were settled by Europeans earlier than other parts of Canada and were subjected to wood harvest prior to the 20th century (Kurz et al., 2013). Those areas would have forestry management legacies of 100 years or more, with the ecosystem carbon cost per unit of wood harvested at or nearing its steady-state and at net sequestration (see Figure 4). For other regions with a more recent forest management history, our results suggest that the ecosystem carbon costs attributed to wood harvesting would result in ecosystem carbon costs higher than the value at 100-years of harvest.

The reference natural disturbance used in all scenarios was wildfire, which is the most widespread and frequent disturbance type in most of Canada's forests. However, other natural disturbance types, most notably insect outbreaks, and locally, windstorms, have also had particularly large impacts on the net emissions of forests between 2002 and 2008 (Stinson et al., 2011), potentially turning Canada's forests in net carbon sources. In fact, climate change itself, through a feedback loop could increase the incidence of both wildfire and insect outbreaks (Kurz et al., 2008). The complex modelling involved in forecasting both climate scenarios and future disturbances in Canadian forests, are out of the scope of this paper but should be considered in future research (but see (Boucher et al., in press)).

The choice of methodological approaches also has an influence on the overall ecosystem carbon costs. A landscape approach was chosen in order to be able to model the forestry carbon dynamics when the specific site of the forest and provenance of harvested wood is unknown. It also allowed for the inclusion of fire disturbance and thus modelled forests were subjected to very small but constant rates of annual fire and harvest disturbances. A similar exercise could have been accomplished using a stand-level perspective, but the detail required to model specific stands would have limited the geographical scope of the results. Also, although forest residues from harvest are typically left on-site in Canada (Thiffault et al., 2015), these could also be collected and thus would be considered a co-product of wood harvesting. The utilization of forest residues for bioenergy, for example, could influence how the ecosystem carbon costs are allocated and thus the result of the ecosystem carbon costs per m^3 of harvested wood.

This work represents a first attempt at modelling the ecosystem carbon costs of harvesting wood across multiple species and regions at the product level. In modelling the forestry ecosystems for most commercially important species across Canada, much of the input forest inventory data was developed using more macro level national forest inventory data and peer-reviewed models. While this data allowed for broad-reaching coverage of most commercial wood, it does have limitations in terms of not having a finer level of detail and granularity that would be expected from the study of a particular forest stand. The model makes use of a theoretical yield curve, which gives a reasonable estimate of the annual biomass accumulation. However empirical forest inventory data for a specific forest stand would almost inevitably better reflect the biomass volume of the forest.

Another limitation is the level of aggregation chosen for the landscapes, across which the temperature and precipitation values have been averaged. Smaller landscapes that more specifically reflect the provenance of harvested wood would allow for more representative mean temperature and precipitation values for the yield curve equations. Furthermore, the wildfire and harvest disturbances are aggregated by ecozone, without considering how those disturbances could affect species differently, while smaller homogeneous fire regimes zones have been shown to better represent the distribution of fire regimes across Canada (Boulanger et al., 2014). Finally, the harvested wood volumes used for calculating the weighted means were calculated, in the absence of more specific statistical data, by combining data from different sources and by using some assumptions to handle data gaps.

The results counter the prevailing assumption of forestry products having a net zero biogenic carbon flux and indicates that carbon footprint and LCA studies should also include the impacts from harvest activities that can further influence the carbon cost of harvested wood. The overall carbon balance of a harvested forest should also consider the carbon content of the wood itself (0.175 - 0.300 $tC{\cdot}m^{-3}$ dry wood). Typically, LCAs of wood products are done from a static point of view. The authors plan to demonstrate how the ecosystem carbon cost results can be integrated into a temporally dynamic life cycle inventory in an upcoming study.

3.3. Validation of results using flux tower measurement data

The validation of the modelling results was carried out by comparing modelled C fluxes of black spruce and jack pine landscapes with flux tower measurement data (Figure 7).

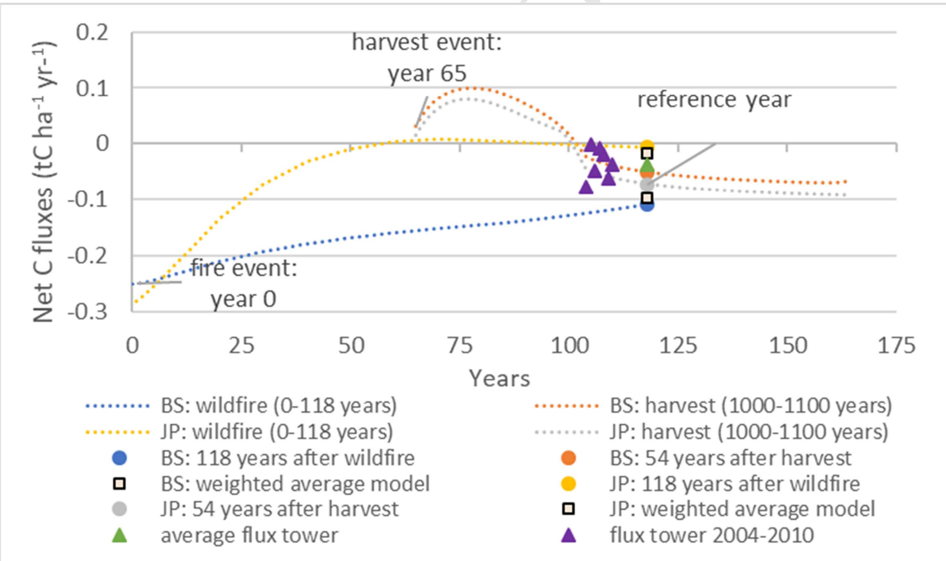


Figure 7 – Modelled scenarios (baseline and harvest) for black spruce (Pinea mariana) and jack pine (Pinus bank-siana) vs. flux tower data. BS = black spruce (Picea mariana), JP = jack spine (Pinus banksiana), wildfire (0-118 years) = landscape affected by annual fire starting from fire event in 1900 to present, harvest (1000-1100 years) =

landscape affected by 100 years of annual fire and harvest following wildfire, 118 years after wildfire = point at present day 118 years after fire, 54 years after harvest = point at present day 54 years after harvest, weighted average model = weighted average of baseline and harvest scenarios, average flux tower = average of flux tower data from 2004-2010, flux tower 2004-2010 = annual averages from 2004-2010. Flux tower data from Fluxnet Canada / Canadian Carbon Program (Coursolle et al., 2012).

The annual flux tower (2004-2010) and the average flux tower data lie at the midpoint between the weighted average of the black spruce and the jack pine modelled results (Figure 7). This demonstrates that despite inherent differences in spatial scales between the two result types, at least for black spruce and jack pine in the Quebec Boreal Shield, the models reflect the ecosystem carbon costs that have been measured at flux tower test sites. As such, the flux tower data provides at least a partial validation of the modelled results. A complete validation of the modelled landscapes would require having access to widespread flux tower data. However, this would be difficult to obtain presently due to the limited geographical scope of the flux tower sites and available length of the measurement record.

4. Conclusion

The ecosystem carbon costs per m^3 of wood harvested in most forest landscapes in Canada shows net sequestration infirming the carbon neutrality assumption. The weighted mean ecosystem carbon costs from a 100-year-old harvested forest, based on harvested volume by species, range from -0.26 to -0.069 $tC{\cdot}m^{-3}$. The spruce species tend to have higher and more variable ecosystem carbon cost scores, while the remaining species tend to have lower scores and less variability. By province, the weighted mean ecosystem carbon costs range from -0.18 to -0.034 $tC{\cdot}m^{-3}$. The Atlantic provinces (New Brunswick and Nova Scotia, in particular) show the most sequestration, whereas the ecosystem carbon costs are highest in the Prairies (Manitoba and Saskatchewan). The mean *time to ecosystem cost neutrality* for each species ranges from 16-60 years. These results show that sustained wood harvest in Canadian forests at current wildfire and harvest rates result in net sequestration benefits. Flux tower measured data at given test sites confirms that simulated results reflect the ecosystem carbon costs. As such, the results of this research work show that harvesting softwood tree species at current rates in Canadian forests, mostly has net carbon sequestration on the forest ecosystem.

Though carbon dynamics of forest management have long been considered in forestry research, this has to the authors' knowledge, not yet been extended to life cycle assessment. Despite the knowledge in the LCA community that biogenic carbon should not be considered neutral, the typical assumption has been that that the carbon sequestered in wood during its growth is the only carbon that has been sequestered, i.e. not considering the effects of wood harvest on the forest ecosystem. By this research work we provided evidence that in addition to account for the sequestration of the carbon embodied in wood, a wood product life cycle assessment should also account for the ecosystem carbon cost.

This research work also demonstrates the feasibility of using a forest carbon budget model to generate regionalized *cradle-to-gate* inventories of forest ecosystem carbon dynamics for harvested wood products across Canada. Together these inventories form a database covering 12 softwood tree species across 10 provinces of the Canadian boreal forest. The database could be used as is within decision-making tools, such as building information models for designing green buildings. These data can also be used as a part of a *cradle-to-grave* life cycle assessment by converting the ecosystem carbon costs into CO_2 emissions and expressing them in a life cycle inventory along with the carbon fluxes occurring at other life cycle stages. In doing so it will be important to evaluate the choice of ecosystem carbon cost values to use within a dynamic life cycle assessment, in order to ensure an equitable allocation of sequestration benefits to the wood users.

Acknowledgements

The authors would like to thank project partners Cecobois, Canadian Wood Council, Desjardins, GIGA, Hydro-Québec and Pomerleau as well as the Natural Science and Engineering Research Council of Canada (CRD 462197-13).

Appendix A: Supplementary material

Supplementary data related to this article can be found at:

References

Beaudoin, A., Bernier, P.Y., Guindon, L., Villemaire, P., Guo, X.J., Stinson, G., Bergeron, T., Magnussen, S., Hall, R.J., 2014. Mapping attributes of Canada’s forests at moderate resolution through kNN and MODIS imagery. Canadian Journal of Forest Research 44(5), 521-532.

Bergeron, O., Margolis, H.A., Black, T.A., Coursolle, C., Dunn, A.L., Barr, A.G., Wofsy, S.C., 2007. Comparison of carbon dioxide fluxes over three boreal black spruce forests in Canada. Global Change Biology 13(1), 89-107.

Bernier, P., Paré, D., 2013. Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. GCB Bioenergy 5(1), 67-72.

Bernier, P.Y., Guindon, L., Kurz, W.A., Stinson, G., 2010. Reconstructing and modelling 71 years of forest growth in a Canadian boreal landscape: a test of the CBM-CFS3 carbon accounting model. Canadian Journal of Forest Research 40(1), 109-118.

Bogdanski, B.E.C., 2008. Canada's boreal forest economy: economic and socioeconomic issues and research opportunities. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre,, Victoria, BC, Canada, p. 59.

Böttcher, H., Kurz, W.A., Freibauer, A., 2008. Accounting of forest carbon sinks and sources under a future climate protocol—factoring out past disturbance and management effects on age–class structure. Environmental Science & Policy 11(8), 669-686.

Boucher, D., Boulanger, Y., Aubin, I., Bernier, P.Y., Beaudoin, A., Guindon, L., Gauthier, S., 2018. Current and projected cumulative impacts of fire, drought and insects on timber volumes across Canada. Ecological applications : a publication of the Ecological Society of America.

Boulanger, Y., Gauthier, S., Burton, P.J., 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. Canadian Journal of Forest Research 44(4), 365-376.

Brandão, M., Levasseur, A., 2011. Assessing Temporary Carbon Storage in Life Cycle Assessment and Carbon Footprinting, JRC Scientific and Technical Reports. JRC of the European Commission.

Brandt, J.P., Flannigan, M.D., Maynard, D.G., Thompson, I.D., Volney, W.J.A., 2013. An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues1. Environmental Reviews 21(4), 207-226.

Burns, R.M., Honkala, B.H., 1990. Silvics of North America: 1. Conifers, Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC, USA, p. 1383.

Cao, V., Margni, M., Favis, B.D., Deschênes, L., 2016. Choice of land reference situation in life cycle impact assessment. The International Journal of Life Cycle Assessment 22(8), 1220-1231.

Cherubini, F., Peters, G.P., Berntsen, T., Strømman, A.H., Hertwich, E., 2011. CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3(5), 413-426.

Christensen, T.H., Gentil, E., Boldrin, A., Larsen, A.W., Weidema, B.P., Hauschild, M., 2009. C balance, carbon dioxide emissions and global warming potentials in LCA-modelling of waste management systems. Waste Management & Research 27(8), 707-715.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J.G., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S., Thornton, P., 2013. Carbon and Other Biogeochemical Cycles, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 465-570.

Coursolle, C., Margolis, H.A., Barr, A.G., Black, T.A., Amiro, B.D., McCaughey, J.H., Flanagan, L.B., Lafleur, P.M., Roulet, N.T., Bourque, C.P.-A., Arain, M.A., Wofsy, S.C., Dunn, A., Morgenstern, K., Orchansky, A.L., Bernier, P.Y., Chen, J.M., Kidston, J., Saigusa, N., Hedstrom, N., 2006. Late-summer C fluxes from Canadian forests and peatlands along an east-west continental transect. Can. J. For. Res. 36, 783–800.

Coursolle, C., Margolis, H.A., Giasson, M.-A., Bernier, P.-Y., Amiro, B.D., Arain, M.A., Barr, A.G., Black, T.A., Goulden, M.L., McCaughey, J.H., Chen, J.M., Dunn, A.L., Grant, R.F., Lafleur, P.M., 2012. Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests. Agricultural and Forest Meteorology 165, 136-148.

Dymond, C.C., 2012. Forest carbon in North America - annual storage and emissions from British Columbia's harvest, 1965-2065. Carbon Balance and Management 7(8), 1-20.

Ecological Stratification Working Group, 1996. A National Ecology Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land Biological Resources Research, and Environmental Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull, p. Report and national map at 1:7 500 000 scale.

Garcia, R., Freire, F., 2014. Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. Journal of Cleaner Production 66, 199-209.

Gauthier, S., Bernier, P.Y., Boulanger, Y., Guo, J., Guindon, L., Beaudoin, A., Boucher, D., 2015. Vulnerability of timber supply to projected changes in fire regime in Canada's managed forests. Canadian Journal of Forest Research 45(11), 1439-1447.

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., Pajula, T., 2013. Approaches for inclusion of forest carbon cycle in life cycle assessment - a review. GCB Bioenergy 5(5), 475-486.

International Organization for Standards, 2006a. ISO 14040: 2006 - LCA- Principles and framework - Environmental management. ISO, Geneva, Switzerland.

International Organization for Standards, 2006b. ISO 14044: 2006 - LCA - Requirements and guidelines - Environmental management. ISO, Geneva, Switzerland.

IPCC, 1997. Revised 1996 IPCC guidelines for national greenhouse inventories, in: Houghton, J.T., Filho, L.G.M., Lim, B., Tréanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callander, B.A. (Eds.). Intergovernmental Panel on Climate Change IPCC/OECD/IEA, Paris, France.

IPCC, 2006. Chapter 2: Generic Methodologies Applicable to Multiple Land-Use Categories, in: Aalde, H., Gonzalez, P., Gytarsky, M., Krug, T., Kurz, W.A., Lasco, R.D., Martino, D.L., McConkey, B.G., Ogle, S., Paustian, K., Raison, J., Ravindranath, N.H., Schoene, D., Smith, P., Somogyi, Z., van Amstel, A., Verchot, L. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Japan, p. 59.

Jarvis, P., Linder, S., 2000. Botany: Constraints to growth of boreal forests. Nature 405(6789), 904-905.

Kauppi, P.E., Rautiainen, A., Korhonen, K.T., Lehtonen, A., Liski, J., Nöjd, P., Tuominen, S., Haakana, M., Virtanen, T., 2010. Changing stock of biomass carbon in a boreal forest over 93 years. Forest Ecology and Management 259(7), 1239-1244.

Keith, H., Mackey, B., Berry, S., Lindenmayer, D., Gibbons, P., 2009. Estimating carbon carrying capacity in natural forest ecosystems across heterogeneous landscapes: addressing sources of error. Global Change Biology, no-no.

Kindermann, G.E., McCallum, I., Fritz, S., Obersteiner, M., 2008. A Global Forest Growing Stock, Biomass and Carbon Map Based on FAO Statistics. Silva Fennica 42(3), 387-396.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., Safranyik, L., 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452(April 2008), 987-990.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., Apps, M.J., 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling 220(4), 480-504.

Kurz, W.A., Shaw, C.H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., Dyk, A., Smyth, C., Neilson, E.T., 2013. Carbon in Canada's boreal forest — A synthesis. Environmental Reviews 21(4), 260-292.

Lemprière, T.C., Kurz, W.A., Hogg, E.H., Schmoll, C., Rampley, G.J., Yemshanov, D., McKenney, D.W., Gilsenan, R., Beatch, A., Blain, D., Bhatti, J.S., Krcmar, E., 2013. Canadian boreal forests and climate change mitigation1. Environmental Reviews 21(4), 293-321.

Lessard, D., 2013. Effet de la transformation d'une forêt naturelle en forêt aménagée sur les bénéfices de séquestration inclus à l'empreinte carbone des produits du bois, Environmental Science. p. 61.

Levasseur, A., Lesage, P., Margni, M., Brandão, M., Samson, R., 2012. Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: comparison of dynamic life cycle assessment with ton-year approaches. Climatic Change 115, 759.

Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment. Journal of Industrial Ecology 17(1), 117-128.

Luyssaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., Papale, D., Piao, S.L., Schulze, E.D., Wingate, L., Matteucci, G., Aragao, L., Aubinet, M., Beer, C., Bernhofer, C., Black, K.G., Bonal, D., Bonnefond, J.M., Chambers, J., Ciais, P., Cook, B., Davis, K.J., Dolman, A.J., Gielen, B., Goulden, M., Grace, J., Granier, A., Grelle, A., Griffis, T., Grünwald, T., Guidolotti, G., Hanson, P.J., Harding, R., Hollinger, D.Y., Hutyra, L.R., Kolari, P., Kruijt, B., Kutsch, W., Lagergren, F., Laurila, T., Law, B.E., Le Maire, G., Lindroth, A., Loustau, D., Malhi, Y., Mateus, J., Migliavacca, M., Misson, L., Montagnani, L., Moncrieff, J., Moors, E., Munger, J.W., Nikinmaa, E., Ollinger, S.V., Pita, G., Rebmann, C., Roupsard, O., Saigusa, N., Sanz, M.J., Seufert, G., Sierra, C., Smith, M.L., Tang, J., Valentini, R., Vesala, T., Janssens, I.A., 2007. CO2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology 13(12), 2509-2537.

Margolis, H.A., Beaudoin, A., Bernier, P.Y., Bigras, F., Paré, D., 2016. Quebec Flux Station – Eastern Boreal Black Spruce. ORNL DAAC.

Margolis, H.A., Flanagan, L.B., Amiro, B.D., 2006. The Fluxnet-Canada Research Network: Influence of climate and disturbance on carbon cycling in forests and peatlands. Agricultural and Forest Meteorology 140(1-4), 1-5.

McKechnie, J., Colombo, S.J., Chen, J., Mabee, W., Maclean, H.L., 2011. Forest bioenergy or forest carbon - Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environ Sci Technol 45, 789-795.

McKenney, D., Pedlar, J., Lawrence, K., Papadopol, P., Allen, D., Yemshanov, D., 2016. Bioclimatic parameters for Canada 1981-2010, 1981-2010 ed. Natural Resources Canada, Sault Sainte Marie, Ontario, Canada.

Muñoz, I., Schmidt, J.H., 2016. Methane oxidation, biogenic carbon, and the IPCC's emission metrics. Proposal for a consistent greenhouse-gas accounting. The International Journal of Life Cycle Assessment 21(8), 1069-1075.

National Forest Inventory, 2013. Stastical Summaries for Terrestrial Ecozones. Canadian Forest Service, v 3.

Natural Resources Canada, 2016. Forest carbon. https://www.nrcan.gc.ca/forests/climate-change/forest-carbon/13085. (Accessed 11/09/2017.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333(6045), 988-993.

Røyne, F., Peñaloza, D., Sandin, G., Berlin, J., Svanström, M., 2016. Climate impact assessment in life cycle assessments of forest products: implications of method choice for results and decision-making. Journal of Cleaner Production 116, 90-99.

Searchinger, T.D., Havlik, P., Oppenheimer, M., Kammen, D.M., Hamburg, S.P., Robertson, G.P., Melillo, J., Likens, G.E., Chameides, W., Lubowski, R.N., Schlesinger, W.H., Obersteiner, M., Tilman, G.D., 2009. Fixing a Critical Climate Accounting Error. Science 326(23 October 2009), 528-529.

Smyth, C.E., Stinson, G., Neilson, E.T., Lemprière, T.C., Hafer, M., Rampley, G.J., Kurz, W.A., 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences 11, 3515–3529.

Stinson, G., Kurz, W.A., Smyth, C., Neilson, E.T., Dymond, C.C., Metsaranta, J., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., Blain, D., 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Global Change Biology 17, 2227–2244.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., Skinner, W.R., 2002. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research 108(D1).

Thiffault, E., Béchard, A., Paré, D., Allen, D., 2015. Recovery rate of harvest residues for bioenergy in boreal and temperate forests: A review. Wiley Interdisciplinary Reviews: Energy and Environment 4(5), 429-451.

Ung, C.-H., Bernier, P.Y., Guo, X.J., Lambert, M.-C., 2009. A simple growth and yield model for assessing changes in standing volume across Canada's forests. The Forestry Chronicle 85(1), 57-64.

Vogtländer, J.G., van der Velden, N.M., van der Lugt, P., 2013. Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. The International Journal of Life Cycle Assessment 19(1), 13-23.

Zald, H.S.J., Spies, T.A., Harmon, M.E., Twery, M.J., 2016. Forest Carbon Calculators - A Review for Managers, Policymakers and Educators. Journal of Forestry 114(2), 134-143.

Zanchi, G., Pena, N., Bird, N., 2010. The upfront carbon debt of bioenergy. Joanneum Research, Graz, Austria, p. 56.

Highlights

- Current harvesting of wood in Canadian forests, has net C benefits to forests
- Results oppose biogenic carbon neutrality methodology for forestry products
- Demonstrates use a forestry carbon budget model for forest ecosystem LCIs