Canadian Journal of Forest Research

Biomass procurement in boreal forests affected by spruce budworm: Effects on regeneration, costs and carbon balance

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2021-0060.R1
Manuscript Type:	Article
Date Submitted by the Author:	16-Jun-2021
Complete List of Authors:	Gouge, Daniel; Laval University, Department of Wood and Forest Sciences Thiffault, Evelyne; Laval University, Department of Wood and Forest Sciences Thiffault, Nelson; Laval University, Department of Wood and Forest Sciences; Natural Resources Canada, Department of Wood and Forest Sciences; Laval University, Department of Wood and Forest Sciences
Keyword:	silviculture, woody debris, cost analysis, microsite, carbon balance
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Abstract

Biomass procured from forests affected by natural disturbances as a bioenergy source is increasingly considered in the context of climate change mitigation. By comparing clearcuts with and without biomass procurement, we aimed to determine the effects of biomass extraction performed alongside lumber harvesting on regeneration density, number of planting microsites, forest renewal costs, and carbon fluxes, in harvested boreal stands affected by spruce budworm. Results showed that biomass procurement increased regeneration density and number of planting microsites. Reduction of downed woody debris due to biomass procurement lowered site preparation costs by 282.07 CAD•ha⁻¹, equivalent to 14.45 CAD per oven-dry metric tonne (odmt⁻¹) of harvested biomass. Product value from biomass processing had to reach from 13.90–76.84 CAD•odmt⁻¹ to make biomass procurement operations profitable. Since biomass procurement significantly increased stocking and reduced the amount of decaying debris, it also reduced cumulative CO₂ emissions relative to scenarios without biomass procurement. However, ensuring forest renewal through site preparation and plantation *per se*, irrespective of biomass procurement, played a more important role for carbon sequestration and net balance. Integrating biomass harvesting to silviculture could have significant ecological and financial impacts on forest management while supporting mitigation efforts against climate change.

Keywords: silviculture; woody debris; cost analysis; microsite; carbon balance; natural disturbances

Introduction

Anthropogenic climate change is a growing concern around the world because of its potentially disruptive effects on ecosystems. Climate change is mainly due to CO₂ emissions driven by human fossil fuel consumption (IPCC 2014); in 2020, CO₂ atmospheric concentration reached 416.18 ppm (US Department of Commerce 2020). The Intergovernmental Panel on Climate Change (IPCC) recommended to stabilize atmospheric concentration of CO₂ at a maximum of 450 ppm from now to 2050 (IPCC 2014). To achieve this goal, the IPCC suggests the use of renewable energies as substitutes for fossil energy sources (IPCC 2014; Bacovsky et al. 2016). Bioenergy from forest biomass could play an important role in the transition of the global energy system towards renewable sources (Bacovsky et al. 2016). Regions with vast boreal forests such as eastern Canada, which possesses large quantities of untapped forest biomass feedstock, including that generated by natural disturbances, could be able to mobilize sustainable forest biomass supply chains in order to contribute to global efforts of fossil fuel replacement (Paré et al. 2016).

Due to the nature and extent of natural disturbances that they undergo, boreal landscapes of eastern Canada do represent distinct challenges for forest management and wood supply. For example, coniferous stands composed of balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) B.S.P.) are affected by cyclical large-scale spruce budworm (*Choristoneura fumiferana* (Clemens)) outbreaks, which occur every 30–40 years. This insect causes severe tree defoliation that leads to growth decline and death of the most affected trees (Fig. 1). Balsam fir mortality due to the last outbreak in the 1980s reduced harvestable fibre volume by 55% in the

province of Quebec, Canada (Archambault and Beaulieu 1985). Wood from affected trees quickly degrades and becomes unsuitable for processing into conventional wood products such as lumber and pulp (Barrette et al. 2015). Large-scale natural disturbances such as spruce budworm epidemics hence cause an influx of low-quality coniferous woods that are ill adapted to current wood markets. Thus, there is a need to develop new markets for this resource, which would help expand silviculture opportunities for landscapes affected by natural disturbances (Aguilar and Garrett 2009; Durocher et al. 2019).

[APPROXIMATE LOCATION OF FIG. 1]

Forest bioenergy represents a potential outlet for degraded or otherwise unused woods (Dymond et al. 2010), as feedstock requirements for energy conversion are less stringent than those of the conventional wood market (Elbersen et al. 2015; Barrette et al. 2015). However, the profitability of bioenergy production might be difficult to achieve in the context of boreal forest biomass supply chains (Barrette et al. 2017). In particular, salvage logging of naturally disturbed forests can incur significant costs (Iranparast Bodaghi et al. 2018). Moreover, the precise benefits of biomass procurement in the form of degraded trees for bioenergy production as a mean to mitigate carbon emissions have been questioned (Laganière et al. 2017). Indeed, the time before a bioenergy system using that type of feedstock can reach lower cumulative carbon emissions than an equivalent fossil fuel-based system can be very long, due to the low energy density of wood and the slow decomposition rate of dead trees.

Nevertheless, there could be an opportunity to improve the financial and carbon balance of woods from naturally disturbed stands, by jointly managing timber and bioenergy production (She et al. 2019). Closer integration of biomass feedstock procurement with other silviculture and harvesting objectives can contribute to the optimization of overall fibre supply, operation costs and long-term carbon balance (Asikainen et al. 2016; Röder et al. 2019). For example, woody debris left on cutblocks can have direct effects on the establishment and growth of forest regeneration (Harrington et al. 2013). The presence of woody debris can decrease the availability of suitable microsites for natural and planted regeneration establishment (Devine and Harrington 2007; Peter and Harrington 2018). Moreover, coarse woody debris can increase fire risk during the first years after harvesting (Harrington et al. 2018). In spruce budworm-affected stands, while sound wood is harvested for lumber, large amounts of debris are left on the site because the proportion of lumber-quality wood is low (Barrette et al. 2017). This might require windrowing, i.e., concentrating debris into rows, so that other site preparation and regeneration treatments can be performed (e.g., scarification, planting). Windrows increase unproductive areas and accumulate nutrients away from the regenerating zones (Zhang et al. 2015). Also, windrows provide habitats for small animals, such as the southern red-backed vole (*Myodes gapperi*) and the long-tailed vole (*Microtus longicaudus*), which can damage newly planted trees (Sullivan and Sullivan 2014).

On the other hand, retention of coarse woody debris on cutblocks can benefit seedling growth and vigour by reducing vegetative competition (Harrington et al. 2018), increasing soil water retention (Trottier-Picard et al. 2014) and providing nutrients for tree growth (Krankina et al. 1999). The ecological role of woody debris generated by harvesting on

seeding establishment and growth will thus likely vary according to site conditions (Trottier-Picard et al. 2014), which underlines the need to further our understanding in specific forestry contexts. The presence and quantity of woody debris on cutblocks can be manipulated with biomass feedstock procurement, which might reduce the need of other silvicultural treatments and associated machinery movements, and hence, influence the overall financial balance of wood and biomass supply. This should also impact the greenhouse gases (GHG) balance of bioenergy produced from biomass that would otherwise end up as woody debris: the reduced machinery movements and the lower amounts of decaying debris can reduce GHG emissions to the atmosphere, while the potential effects on regeneration growth can increase carbon sequestration.

Our objective was to evaluate the effect of biomass procurement as a component of a larger forest management system that aims to i) provide feedstock for softwood lumber and bioenergy and ii) ensure forest regeneration after harvesting. We used boreal stands that were affected by a recent spruce budworm outbreak in northeastern Quebec (Canada) as a case study. We specifically aimed to determine the effects of forest biomass procurement, performed along with harvesting for lumber, on regeneration, planting microsites and site preparation needs in harvested cutblocks of these stands. We characterized treatment effects on mineral soil depth, humus thickness, substrate type, natural regeneration and competing vegetation conditions. The financial costs and carbon balance of biomass procurement were also assessed.

We hypothesized that the decrease in woody debris volumes associated with biomass procurement would result in greater mineral soil exposition; this should generate more

suitable microsites for regeneration establishment, and hence, reduce the needs for further site preparation. We also posited that by facilitating seedling establishment and reducing the needs for site preparation, biomass procurement would incur significant financial cost reductions in forest renewal operations. This would also improve the carbon balance for bioenergy.

Materials and Methods

Study region

We conducted our study in the Côte-Nord region of Quebec, Canada, 25 km northwest of the city of Port-Cartier along the Saint Lawrence River and on the southern limit of the Boreal Shield (50° 4' 5,136" N, 67° 2' 56,997" W; Fig. 2). Based on the nearest meteorological station (Pentecôte: 49° 44' 4" N, 67° 10' 27" W), the area has a mean annual temperature of 2.4 °C and average precipitation of 1211.4 mm year⁻¹, of which 26% falls as snow. The study area is located in the black spruce–feathermoss bioclimatic domain of Quebec (Saucier et al. 2009). The elevation of the study area varies between 70 m and 250 m; the topography is characterized by high hills and mountains, and steep slopes are frequent, with an average of 11% slope for the study sites. Shallow glacial till is the most frequent surficial deposit, but rock outcrops revealing the Precambrian Grenville bedrock are also abundant. Black spruce stands growing on podzolized soils dominate the landscape. Balsam fir and white birch (*Betula papyrifera* Marshall) are found on hillsides and are sometimes accompanied by white spruce (Bouchard and Pothier 2011). There is also a small proportion of tamarack larch (*Larix laricina* (Du Roi) Koch.), jack pine (*Pinus banksiana* Lamb.), and trembling aspen (*Populus tremuloides* Michx.), mixed with other

species. The understory is characterized by various species of shrubs, ericaceous species, lichens and mosses (Hins et al. 2009).

As a result of abundant precipitation, the region is characterized by long fire intervals (Bouchard et al. 2008), which favour the abundance of balsam fir, relative to other boreal regions (Bouchard and Pothier 2008). This explains the relatively high occurrence of this species among stands of the study area, as well as stand susceptibility to spruce budworm outbreaks. This susceptibility is exemplified by the relatively high average level of mortality among stands of the study area (evaluated with Hunter classes that express the level of tree vitality and decay; an average Hunter class close to 3 indicates that most trees have $\geq 80\%$ of dead foliage and are hence dying (Hunter and Malcolm 1990)). Based on a preliminary survey conducted in 10 uncut forest stands within the case study area, balsam fir represents 50% of merchantable-sized stems, followed by black (47%) and white (2%) spruces. Other conifers and white birch each represent less than 1% of the commercial species. In the study area, stands average 14 m in height and $187 \text{ m}^3 \bullet \text{ha}^{-1}$ of commercial standing lumber volume.

Experimental design and treatments

The experimental design consisted of 28 randomly chosen cutblocks located within an area of 651 ha that was clearcut harvested for lumber in 2018 and 2019, with some cutblocks having also been subjected to biomass procurement (Fig. 2). Half of the selected cutblocks had been subjected to both lumber and forest biomass procurement. In this treatment, degraded coniferous trees and tree parts that did not meet lumber standards, as well as

whole trees classified as intolerant hardwoods, were harvested and directed to bioenergy. The other half of the cutblocks had been subjected to lumber procurement only, with harvesting of lumber-quality coniferous trees and tree parts. For this treatment, remaining trees and tree parts were left on site, mostly as downed woody debris. Cutblocks were selected by ensuring a minimal distance of at least 200 m between them. The selected cutblocks covered a range of ecological types (i.e., balsam fir–black spruce potential vegetation on thin to medium mineral deposit and, respectively, coarse texture and fast drainage, medium texture and moderate drainage, and coarse texture and subhydric drainage (Morneau and Landry 2010)). Ecological types were represented equally among cutblocks with and without biomass procurement. We randomly located a sample plot (Fig. 3) in each cutblock, thus creating a completely randomized design comprising 14 replicates of each treatment (with and without biomass procurement). All 28 plots were measured approximately five months after harvesting (either in 2018 or 2019).

[APPROXIMATE LOCATION OF FIG. 2]

Downed woody debris and harvested biomass

In each sample plot, we established two orthogonal, 20-m long transects and tallied downed woody debris that intersected the transects. Each debris was either classified as small (diameter = 1.1 cm to 5 cm) or coarse (diameter > 5 cm). Small woody debris were tallied on four 5-m long subsections of the entire transects (Fig. 3); we noted the average decay Hunter class and dominant species of debris in each subsection of the transects. Coarse woody debris were tallied over the total length of the two 20-m transects. Diameter, species and decay Hunter class were recorded for each piece of tallied coarse downed woody

debris. Based on these measures, average volumes and masses per hectare of woody debris were calculated for each plot, using equations and a wood density chart for Canadian species (NFI 2010). Since data related to harvested products were not available, the average amount of harvested biomass had to be inferred indirectly. It was calculated by subtracting the average amount of downed woody debris found on cutblocks subjected to biomass procurement from the average amount found on cutblocks without biomass procurement.

[APPROXIMATE LOCATION OF FIG. 3]

Pre-harvest forest cover, regeneration and microsites

We estimated pre-harvest forest cover density using governmental forest maps for the study area, and further validated stand density based on the number of stumps (see below). Pre-harvest forest cover density was categorized into four classes ($\geq 25\%$ and $< 40\%$; $\geq 40\%$ and $< 60\%$; $\geq 60\%$ and $< 80\%$; $\geq 80\%$ (Berger et al. 2015)).

Stocking of natural regeneration was evaluated in ten circular 5 m² microplots distributed along the transects in each sample plot (Fig. 3). Seedlings were considered only if they met regional standards for potential tree crop (Appendix A), i.e., healthy, straight (maximum inclination of 30%), free to grow and with a minimum height of 15 cm. According to regional wood markets, desired species for sawtimber were black spruce, white spruce, balsam fir, tamarack larch and jack pine; together these species represent about 86% of the feedstock for sawmills (Ministère des Forêts de la Faune et des Parcs 2020).

The presence of suitable plantation microsites was evaluated in each microplot based on operational criteria adapted from provincial inventory guidelines (Méthot et al. 2014; Méthot and Auger 2016). A microsite was considered only if it was entirely located within the microplot and if it had a minimum area of 20 cm × 20 cm. A value of 100% seedling or microsite stocking meant that suitable microsites and/or desired regeneration were found in all ten microplots; for regeneration, this translates into a density of at least 2000 seedlings•ha⁻¹. The following standards were used to identify a suitable microsite for plantation:

- Humus thickness ≤ 5 cm (excluding the easily removable part with a boot);
- Adequate light availability for the conifer species, based on their autecology;
- Presence of humus at a maximum distance of 1 m around the microsite;
- Soil with aerobic conditions and suitable drainage for the planted species;
- Mineral soil thickness ≥ 15 cm;
- Free of obstacles like woody debris, stumps, rocks and severe soil depressions.

Surface substrate and competing vegetation

The dominant substrate category and depth were recorded at the centre of each microplot using the following categories; humus, mineral soil, stones, bedrock, decaying wood or buried wood. Percent cover and dominant species of competing vegetation were inventoried over the area of each microplot.

Operational constraints to site preparation

We evaluated operational constraints to site preparation within each plot according to provincial and regional standards (Appendix A). The number of standing trees was tallied within the 400 m² plots. Soil depth to bedrock, % slope, presence of obstacles, stoniness and trafficability were also estimated. Stumps were tallied within a 4.99 m-radius concentric subplot. For each stump, species, height, top diameter and decay Hunter class were recorded.

Statistical analyses

All analyses were done within the R statistical environment v3.5.3 (R Core Team 2019). We used mixed effects linear models with function lme of the package nlme (Pinheiro et al. 2020) to estimate biomass procurement (with or without) and pre-harvest forest cover density effects on microsite and regeneration variables, i.e., stocking of suitable microsites and desired regeneration. These analyses were performed at the plot level, as presence/absence values from the 10 subplots within a given plot were used to calculate stocking values for each plot. Cutting year (2018 or 2019) and ecological types were used as random variables. Using data at the plot level (average of the 10 subplots), we then compared the effects of biomass procurement on woody debris volume and competing vegetation cover using the same mixed model. We further investigated relationships between site preparation costs, volume of harvested woody debris and volume of residual downed woody debris left on felling areas using simple correlations based on the Kendall method due to the small sample size and zero inflated data (Bonett and Wright 2000). Prior to analyses, we verified if there was autocorrelation using correlation plots as well as residue distribution with standard graphical approaches. In all cases, we used $p = 0.05$ as a threshold for significance.

Financial analysis

Using a similar approach to Barrette et al. (2017) and Béland et al. (2020), we performed a financial analysis of forest biomass procurement by estimating the costs of wood and biomass harvesting and transportation, site preparation and plantation. Silviculture costs (in CAD•ha⁻¹) were estimated based on information provided by regional companies and provincial standards for silviculture (Bureau de mise en marché des bois 2019) (Table 1). For estimating site preparation costs based on plot data, we carried out an analysis based on inventory data, regional standards and industrial/regional practices (Appendix A); we assumed that site preparation and plantation would be performed on cutblocks for which regeneration stocking was $\leq 60\%$.

[APPROXIMATE LOCATION OF TABLE 1]

Skidding traffic is known to decrease regeneration growth (Zenner et al. 2007). We assumed that skidding trails (which, by provincial regulations, occupy a maximum of 25% of cutblock area, thus representing a quarter of the total cost per ha) would need to undergo mechanical site preparation if the overall stocking of desired regeneration (15 cm height) was $> 40\%$ and $\leq 60\%$. The choice of machinery was based on field characteristics and subsequent planned treatments.

Biomass supply costs were estimated assuming an average harvested mass of 19.52 oven-dry metric tonnes (odmt) of biomass per hectare, calculated from the difference of downed

woody debris mass between plots with and without biomass procurement. Machinery productivity and costs were estimated based on data provided by companies and the Quebec Wood Marketing Office (Groupe DDM 2016) (Table 2). Harvesting productivity was constant over all cutblocks. An average transport distance was estimated from the regional forest map using ArcGIS v.10.4 (Esri Canada, Toronto, Ontario), and assuming that sawtimber and biomass processing plants were co-located in the city of Port-Cartier, the main industrial hub in the region (see Fig. 2). We did not consider the additional road maintenance costs that could be attributable to wood transportation for bioenergy uses, as these extra costs are likely to be small relative to overall operation costs (Béland et al. 2020).

[APPROXIMATE LOCATION OF TABLE 2]

The financial analysis was made from an optimistic and a pessimistic perspective. In the optimistic perspective, high-quality trees are harvested for lumber; degraded and low-quality trees are cut and put down to facilitate harvesting machinery movement or for visual assessment of wood quality by the operator; they are thus left as downed woody debris in the absence of biomass procurement. Harvesting costs for all trees are therefore incurred by lumber procurement, whether or not biomass is procured, i.e., there is no additional cost associated with cutting trees for the biomass procurement treatment. The only additional cost imputed to the biomass procurement treatment is that of biomass skidding to the roadside, along with biomass loading and transportation for processing. This represents the current industrial practices occurring in the study area. For the pessimistic perspective, the costs for cutting trees that are specifically procured for biomass are included as part of the

total costs of biomass procurement. This perspective represents a situation in which a degraded forest would be harvested almost exclusively for biomass supply.

Carbon balance analysis

A simple carbon balance analysis was performed to estimate the differences in carbon fluxes associated with ecosystem processes and machinery movement between scenarios with and without biomass procurement. Carbon balance was calculated on the basis of the production of one gigajoule (GJ) of energy, with all flux data computed in kg CO₂-eq•GJ⁻¹. Fluxes were simulated over a 100-year period, and presented as cumulative balance, i.e., annual fluxes were summed up over a given period. Four scenarios were simulated:

1. Biomass procurement for bioenergy, without site preparation and planting (i.e., only natural regeneration);
2. Biomass procurement for bioenergy, with site preparation and planting;
3. No biomass procurement, no site preparation, no planting (i.e., only natural regeneration);
4. No biomass procurement, with site preparation and planting.

An average of 19.52 odmt of biomass was assumed to be procured per hectare, based on field data (see above). The energy density of biomass was assumed to be 16.1 GJ•odmt⁻¹. Assuming a 50% concentration of carbon for biomass and 3.667 kg CO₂-eq per kg of carbon, the amount of CO₂-eq emission associated with the production of 1 GJ of bioenergy from biomass was estimated at 113.9 kg CO₂-eq•GJ⁻¹. Equations describing carbon dynamics in forest ecosystems were adapted from the Carbon Budget Model of the Canadian Forest Service (CBM-CFS) (Kurz et al. 2009) as well as the conceptual

framework for calculating time to carbon parity of forest bioenergy systems of Laganière et al. (2017). Tree growth was modelled according to equations for Canadian species in Ung et al. (2009) and fitted according to curves from Hill (1910). For scenarios with natural regeneration, the simulated stands were assumed to be composed of 50% balsam fir and 50% black spruce. Stand productivity was adjusted to reflect the average seedling stocking after clearcut with or without biomass procurement, as measured in sample plots, i.e., the growth curve was multiplied by the average % seedling stocking. For scenarios with site preparation and planting, the simulated plantations were assumed to be 100% black spruce (following regional practices), with a 100% stocking.

Decay of organic material was simulated according to an exponential decay function:

$$(1) \quad C_{t\text{OM}} = C_{0\text{OM}} \times e^{-kt}$$

where $C_{t\text{OM}}$ is the quantity of carbon stored in organic material at time t (years), $C_{0\text{OM}}$ is the initial quantity of carbon stored in organic material, and k is the decomposition rate of organic material (in year^{-1}). The temperature-dependent function of Kurz et al. (2009) was used to compute the decay rate:

$$(2) \quad k = \text{BDR}_k \times \text{TempMod}$$

where BDR_k is the base decomposition rate of organic material on the ground at a reference mean annual temperature (REFMAT) of 10 °C, and TempMod is the temperature modifier that reduces the decay rate, calculated as:

$$(3) \quad \text{TempMod} = e^{((\text{MAT}_f - \text{REFMAT}) \times \ln(Q_{10}) \times 0.1)}$$

where MAT_f is the mean annual temperature of the simulated forest area, and Q_{10} is the temperature sensitivity of decomposition, set at 2. The mean annual temperature was set at 2.4 °C. In the absence of more detailed information about decomposition rates in the study

region, two base decay rates were tested for downed woody debris, based on data from Kurz et al. (2009): 0.0374 yr^{-1} corresponding the 'Medium dead organic matter', and 0.015 year^{-1} , corresponding to 'Above-ground slow' carbon pool.

Estimated GHG emissions related to site preparation, seedling production and plantation were adapted from Timmermann and Dibdiakova (2014); they were set to $0.056 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$, $0.109 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$ and $0.010 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$, respectively.

While the main interest of scenario comparison was ecosystem processes and site regeneration, complete energy systems were also compared (Appendix B). We assumed a simple system in which biomass would be chipped and used for bioheat production, whereas the fossil energy reference systems (in which no biomass procurement would occur) would be based on heavy oil (the most common energy source for industrial and institutional buildings in Quebec). Estimations for emissions related to biomass procurement (harvesting and skidding), comminution and transport to the bioenergy plant were derived from the FPInterface model¹. Estimated emissions for harvesting+skidding, comminution and transport to bioheat plant (assuming a distance of 50 km back and forth) were $2.63 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$, $0.76 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$ and $0.60 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$, respectively. Emissions of biomass combustion were set at $113.9 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$. Emissions of fossil energy production and use were estimated based on the GHGenius model²; the values were respectively 22.4 and $74 \text{ kg CO}_2\text{-eq}\cdot\text{GJ}^{-1}$ for heavy oil. The conversion efficiency of the

¹ http://fpsuite.ca/l_fr/fpinterface.html

² <https://ghgenius.ca>

boiler was assumed to be the same for both bioheat and fossil systems. Emissions related to wood harvesting and transport for lumber were not calculated, as they were assumed to be the same for all scenarios.

Results

Woody debris, regeneration and plantation microsites

The average volumes of woody debris (including coarse and fine woody debris) for cutblocks without and with biomass procurement were significantly different ($p < 0.001$) and were estimated to be $129.41 \text{ m}^3 \bullet \text{ha}^{-1}$ and $71.68 \text{ m}^3 \bullet \text{ha}^{-1}$, respectively (i.e., 43.08 and $23.56 \text{ odmt} \bullet \text{ha}^{-1}$). On cutblocks subjected to biomass procurement, the ground surface substrates were comprised on average of 12% less downed wood, 11% more humus and 1% more mineral soil than on cutblocks without biomass procurement. The mean percent cover of competing vegetation was 15% across cutblocks, with no significant difference associated with biomass procurement ($p = 0.966$).

When biomass procurement was applied, we observed a significant increase of desired regeneration stocking (+15%), plantation microsite presence (+14%) and combined microsites/regeneration presence (+19%), compared to control (no biomass procurement) conditions (Table 3).

[APPROXIMATE LOCATION OF TABLE 3]

Site preparation needs

The average cost of site preparation in plots without biomass procurement was estimated at 464.06 CAD•ha⁻¹; for plots submitted to biomass procurement, the cost was estimated at 181.99 CAD•ha⁻¹. The reduction of site preparation costs associated with biomass procurement was therefore estimated at 282.07 CAD•ha⁻¹. Overall, biomass procurement led to a cost reduction of forest renewal of 14.45 CAD•odmt⁻¹ of harvested biomass (assuming an average biomass recovery of 19.52 odmt•ha⁻¹, based on the subtraction of the average amount of downed woody debris on cutblocks subjected to biomass procurement from the average amount found on cutblocks without biomass procurement). Those cost savings were mainly attributable to lower needs of woody debris clearance, scarification and plantation.

Site preparation according to biomass volume

There was no significant relationship between site preparation costs and the volume of harvested biomass (Fig. 4A). On the other hand, we observed a significant positive relationship between the residual volume of downed woody debris on cutblocks and site preparation costs (Fig. 4B). However, variability was high, making the degree of association (Kendall rank) close to 0, indicating a somewhat weak correlation.

[APPROXIMATE LOCATION OF FIG. 4]

Supply costs

The total biomass supply costs were estimated by adding tree harvesting (for the pessimistic perspective), collecting, forwarding and transportation costs, and subtracting cost savings in site preparation (Table 4).

[APPROXIMATE LOCATION OF TABLE 4]

According to this estimation, the total cost per odmt of biomass at the processing mill yard was more than three times higher for the pessimistic than for the optimistic perspective, that is, when the full cost of cutting down degraded trees is attributed to biomass procurement (pessimistic) instead of considering that degraded trees are put down in the process of harvesting trees for lumber (optimistic). Factoring in the cost savings associated with reduced needs of site preparation and plantation due to biomass procurement (equivalent to 14.45 CAD•odmt⁻¹) caused a decrease in supply costs of 16% and 51% for the pessimistic and optimistic perspectives, respectively.

Cumulative carbon balance

Our first analysis of cumulative carbon balance considered only processes associated with dynamics on the forest site (see Appendix B), i.e., stand growth, woody debris decay and site preparation operations, cumulated over a 100-year period (Fig. 5). A scenario without biomass procurement, relying on natural regeneration (no site preparation and no plantation) and assuming a medium decay rate of debris, would be a constant net source of carbon emissions (positive values). On the other hand, scenarios with biomass procurement appeared to create the largest CO₂ sink (negative values), mainly due to the

absence of debris decomposition (Fig. 5). Site preparation and plantation tended to increase carbon sequestration. However, the assumed decay rate of woody debris left on site in scenarios without biomass procurement (either spread on the cutblock in scenarios without site preparation, or pushed into windrows in scenarios with site preparation) had a considerable impact on their cumulative carbon balance. When a slow decay rate was assumed, carbon emissions from debris decomposition were spread over a long period, and did not counteract carbon sequestration from tree growth.

[APPROXIMATE LOCATION OF FIG. 5]

When considering the complete energy systems (Appendix B) (i.e., including biomass procurement, transport, chipping and direct burning for the bioenergy production scenarios, and fossil energy production and combustion for fossil energy production scenarios), similar trends were observed (Fig. 6). Both bioenergy scenarios (with site preparation + plantation, and without, i.e., natural regeneration) started with the highest emissions due to the low energy density of biomass, which causes higher CO₂ emissions per unit of energy during combustion.

[APPROXIMATE LOCATION OF FIG. 6]

Although all scenarios were CO₂ emitters for most of the simulation horizon, the bioenergy scenario based on biomass procurement coupled with site preparation and plantation became a net cumulative CO₂ sink at year 62 and provided the highest cumulative sequestration at year 100. Bioheat production without site preparation, although never a net

sink, caused lower cumulative CO₂ emissions than heavy oil-based scenarios from year 16 and onward, when a medium decay rate was assumed for debris left on site in the absence of biomass procurement, and from year 21 when a slow decay rate was assumed.

Discussion

Regeneration and site preparation

Our results suggest that biomass procurement in the form of degraded trees significantly increases density of regeneration and plantation microsites in felling areas of boreal stands affected by spruce budworm, on which woody debris load is high (an average of 129.41 m³•ha⁻¹ in our study). Regeneration density and microsite stocking were higher on sites that underwent biomass procurement along with timber harvesting as observed elsewhere (e.g., Fleming et al. 2006). The high stocking of seedlings and suitable planting microsites that we measured suggests that an in-fill plantation treatment to supplement natural regeneration would be feasible to achieve a stocking of 100% (about 2000 seedlings•ha⁻¹). Moreover, the average stocking of desired regeneration was above 60% in cutblocks that underwent biomass procurement; site preparation and plantation are usually not required in that context in Quebec, which translates into higher financial savings.

We calculated that biomass procurement could lead to savings of 282.07 CAD•ha⁻¹ due to reduced needs for site preparation and plantation in felling areas. This translated into a saving of 14.45 CAD•odmt⁻¹ of harvested biomass. This was mainly due to two factors: first, the increase in natural regeneration density reduced the need for artificial regeneration

through site preparation and plantation; second, the treatment reduced the need for woody debris clearance with a bulldozer, which is an expensive treatment.

Biomass procurement reduced the presence of woody debris presence on felling areas, which allowed to expose humus substrate on the ground surface. However, the exposure of mineral soil, which is part of suitability criteria of planting microsites in boreal forests (Thiffault 2016; Henneb et al. 2019), was not significantly increased. This is probably due to the presence of a very thick humus layer in those type of forests that persists even after several skidder passages. Thus, humus thickness was often the decisive criterion that downgraded the suitability of planting microsites.

There are two main issues related to the effects of forest biomass procurement on tree growth and forest productivity. First, removing woody debris can increase competing vegetation cover (Harrington et al. 2018). Second, removing too much organic material from felling areas can generate nutrient deficiencies for regeneration and affect tree growth (Krankina et al. 1999). We did not observe significant effects of biomass removal on the competing vegetation cover; however, since measurements were performed shortly after harvesting, it is possible that any impact on other vegetation might not be fully realized yet. Also, the fact that there was still a large amount of residual woody debris left on cutblocks that underwent biomass procurement ($71.68 \text{ m}^3 \cdot \text{ha}^{-1}$, i.e., $23.56 \text{ odmt} \cdot \text{ha}^{-1}$, representing 55% of the initial volume of the stands that were left on the cutblock) suggests that nutrient availability and water retention should not be a major concern in this context (Priewasser et al. 2013; Trottier-Picard et al. 2014).

528

529 *Prediction of cost savings*

530 Our results suggest that it is difficult to predict site preparation costs in relation to harvested
531 or residual woody debris volume. This is likely due to the high variability of both woody
532 debris volume and the several factors that determine site preparation costs. Nevertheless,
533 we did observe a significant, albeit weak, relationship between residual woody debris
534 volume and site preparation costs. Our regression suggests that site preparation would cost
535 approximately 3.59 CAD for each m^3 (or $10.83 \text{ CAD} \cdot \text{odmt}^{-1}$) of woody debris left on
536 site. Biomass procurement could thus contribute to reduce site preparation costs. There are,
537 however, other economic and ecological constraints to consider. First, biomass supply costs
538 can become exponentially higher when harvesting a higher proportion of woody debris on
539 the same cutblock (Yemshanov et al. 2014). Indeed, harvesting the last volume of woody
540 debris on the cutblock would take significantly more time for relatively small gains of
541 biomass volume, which would mitigate the profitability of the operation. Second, it would
542 not be recommended to harvest a high proportion of biomass in felling areas because it
543 could generate long-term nutrient deficiencies in soils (Krankina et al. 1999). Nevertheless,
544 the same concern could occur without biomass procurement if woody debris were disposed
545 in windrows, as windrowing could also generate nutrient deficiencies (Morris et al. 1983).

546

547 *Financial analysis*

548 We hypothesized that biomass supply costs would be lower if savings related to reduction
549 in site preparation needs would be factored in, and if biomass procurement would be
550 integrated into forest operations for timber, thus causing no additional harvesting costs or

productivity losses. Our results suggest that under a pessimistic perspective in which degraded trees would be cut for the sole purpose of biomass procurement, the cost of biomass feedstock would be 91.29 CAD•odmt⁻¹, or 76.84 CAD•odmt⁻¹ if site preparation + plantation savings are included. Such a cost would likely still lead to unprofitable operations for most bioenergy products. For example, Canada is a major supplier of wood pellets to Europe; the value of this product has been estimated at 160 USD•odmt⁻¹ (223.97 CAD•odmt⁻¹) (Barrette et al. 2017). With a pellet production cost of around 55 USD•odmt⁻¹ (76.98 CAD•odmt⁻¹) and an exportation cost to the Netherlands of around 57 USD•odmt⁻¹ (79.77 CAD•odmt⁻¹) (Barrette et al. 2017), using degraded trees as feedstock in a pessimistic scenario would not be financially viable. On the other hand, leaving degraded stands could lead to even greater long-term losses if it hinders forest regeneration and would thus impact future long-term financial returns of forest management. Salvage logging operations in disturbed forests could help recover economic value from timber while also reducing risks of further disturbances in coniferous forests (e.g., wildfire) (Kärhä et al. 2018). Cutting degraded stands for biomass could only be more advantageous for small transportation distances, or for higher-value products (Béland et al. 2020).

Under the optimistic perspective, we assumed that degraded trees would be cut and put down as part of harvesting operations that procure timber-quality wood, to facilitate harvesting machinery movement and for visual assessment of wood quality by the operator. This is the current situation in stands affected by spruce budworm in northeastern Quebec, where forest management is driven by sawmill needs. In this context, the cost of putting down degraded trees could be assumed to be absorbed by timber production. Biomass

feedstock procurement costs would be limited to biomass collecting, forwarding and transport. It would thus average 28.35 CAD•odmt⁻¹, and 13.90 CAD•odmt⁻¹ if site preparation + plantation savings are taken into account. With such a cost, in the context of wood pellets exportation to the Netherlands, the difference between revenues and costs would be positive, with a profit of 53.32 CAD•odmt⁻¹.

However, in a real-life setting of jointly managed operations, the costs of putting down degraded trees would likely be shared between timber and biomass. Biomass procurement costs would thus be somewhere between our pessimistic and optimistic perspective. Nevertheless, this highlights the fact that timber, bioenergy, and silviculture should be managed and analysed jointly (She et al. 2019). Synergies can be found among silvicultural and operational objectives that can contribute to the profitability of the whole forest product value chain (Béland et al. 2020).

Carbon balance

Finally, we hypothesized that by facilitating seedling establishment and reducing the needs for site preparation, biomass procurement would lead to lower CO₂ emissions. Since biomass procurement significantly increased stocking and reduced the amount of decaying debris, it also reduced cumulative CO₂ emissions relative to scenarios without biomass procurement. However, ensuring optimal stand productivity through site preparation and plantation *per se*, irrespective of biomass procurement, plays a more important role for carbon sequestration.

When analyzing the GHG dynamics of the complete energy system over 100 years, biomass procurement for bioenergy production without further site preparation and plantation treatments would not be carbon neutral. This is due to the higher initial CO₂ emissions related to bioenergy production and use, compared to fossil fuels (Laganière et al. 2017). Our results suggest that hypotheses related to the decay rate of debris left on site (either spread on the cutblock or piled in windrows) in the absence of biomass procurement have a major influence on the relative performance of biomass-based systems vs. fossil systems. It is likely that debris in windrows would decay more slowly than when they are spread on the cutblock (Spaulding and Hansbrough 1944), which increases their contact area with the ground and ambient air. Further research is needed to properly assess and quantify the dynamics of debris in such ecosystems. We also did not consider the potential loss of productive forest area due to windrows in scenarios without biomass procurement, which could further reduce overall CO₂ sequestration on forest sites.

As was shown in other studies (e.g., Laganière et al. 2017), the type of fossil fuel displaced by bioenergy likely plays an important role in the overall carbon balance. Displacing more GHG-intensive fossil fuels (such as heavy oil) with biomass increases the relative carbon benefits of bioenergy systems. Conversely, displacing more GHG-efficient fossil fuels (such as propane, which has emissions from production and use of 15 and 61 kg CO₂-eq•GJ⁻¹ according to GHGenius) with biomass would reduce the relative carbon benefit of bioenergy.

Conclusion

Our results suggest that biomass procurement for bioenergy in degraded boreal forests (performed alongside timber harvesting) can serve as a silviculture tool for ensuring the creation of suitable microsites for regeneration of coniferous species. This could lead to a reduction in costs of site preparation and could contribute to decrease carbon emissions. However, cutting entire degraded forests only for biomass procurement does not appear to be financially profitable; it would also not be recommended from a carbon balance point of view. In the context of forest management of public lands in boreal eastern Canada, timber harvesting, biomass procurement, and forest renewal are generally planned, performed and paid for by different stakeholders (the forest product and bioenergy sectors mainly operating separately, and the government assuming costs for silviculture). The benefits of integrating timber and biomass procurement with silvicultural goals described here would, therefore, only become apparent in a context of close collaboration among stakeholders and discussion for cost and silvicultural credit sharing. The synergies leading to financial savings and improved carbon balance could likely be more readily observed on private forest lands.

Although there are some limitations to our study (e.g., assumptions related to costs, simplification of ecological processes), our results support that biomass procurement can be more profitable and lead to higher GHG savings than previously thought, as long as it is included within larger forest management systems. Forests affected by natural disturbances such as the ones studied here might be considered an extreme case for demonstrating the benefits of such an integration. Nevertheless, in other types of forests, various kinds and amounts of underutilized wood can also be found; future changes in the forest product industrial sector could cause certain species and qualities of wood to become in need for

new markets. Bioenergy, especially in the form of higher-value products, could likely provide the agility that is needed to meet silvicultural and management goals.

Acknowledgements

We thank Denis Villeneuve, Éric Harvey and their team from Groupe Rémabec for the support and information provided during every step of the study. We are also grateful to Michel Fortin from Rexforêt, who helped with the planning of the experimental design according to regional standards. We also extend a special thank you to Marius Legendre from La Nord-Côtière for information regarding plantation costs, to Dr. Julie Barrette for commenting an earlier version of the manuscript, and to the Associate Editor and reviewers for insightful suggestions. Finally, we are indebted to Claudie-Maude Canuel and Mathieu Béland for their help in field work.

Competing interests statement

The authors declare there are no competing interests.

Contributor's statement

Daniel Gouge: Conceptualization, Methodology, Mathematical and statistical analysis, Software, Data curation, Investigation, Visualization Writing and Editing. Evelyne Thiffault: Supervision, Funding, Reviewing. Nelson Thiffault: Supervision, Funding, Reviewing.

Funding statement

This study was funded by a Natural Science and Engineering Research Council of Canada grant from the Engage program (Grant number: EGP #533588-18; PI: Évelyne Thiffault; industrial partner: Arbec) and the Canadian Wood Fibre Centre of Natural Resources Canada (PI: Nelson Thiffault). E. Thiffault also received financial support from the International Energy Agency Bioenergy – Task 43. N. Thiffault received additional financial support from Natural Resources Canada – Regional Science Supporting the Forest Bioeconomy.

Data availability statement

The data used in this work are openly available at https://figshare.com/articles/dataset/Gouge_et_al_Biomass_procurement/14785074

References

- Aguilar, F., and Garrett, H.E. 2009. Perspectives of woody biomass for energy: Survey of state foresters, state energy biomass contacts, and National Council of Forestry Association executives. *J. For.* **107**(6): 297–306.
- Archambault, L., and Beaulieu, J. 1985. Réduction de croissance en volume occasionnée au sapin baumier, suite à la défoliation par la tordeuse des bourgeons de l'épinette. *For. Chron.* **61**(1): 10–13. doi:10.5558/tfc61010-1.
- Asikainen, A., Ikonen, T., and Routa, J. 2016. Challenges and opportunities of logistics and economics of forest biomass. *In* Mobilisation of Forest Bioenergy in the Boreal and Temperate biomes. *Edited by* E. Thiffault, G. Berndes, M. Junginger, J.N. Saddler, and C.T. Smith. Elsevier. pp. 68–83. doi:10.1016/B978-0-12-804514-5.00005-6.
- Bacovsky, D., Ludwiczek, N., Pointner, C., and Verma, V.K. 2016. IEA Bioenergy Countries' Report: Bioenergy policies and status of implementation. doi:10.2172/1326902.
- Barrette, J., Thiffault, E., Achim, A., Junginger, M., Pothier, D., and De Grandpré, L. 2017. A financial analysis of the potential of dead trees from the boreal forest of eastern Canada to serve as feedstock for wood pellet export. *Appl. Energy* **198**: 410–425. doi:10.1016/j.apenergy.2017.03.013.
- Barrette, J., Thiffault, E., Saint-Pierre, F., Wetzal, S., Duchesne, I., and Krigstin, S. 2015. Dynamics of dead tree degradation and shelf-life following natural disturbances: can salvaged trees from boreal forests “fuel” the forestry and bioenergy sectors? *Forestry* **88**(3): 275–290. doi:10.1093/forestry/cpv007.
- Béland, M., Thiffault, E., Barrette, J., and Mabee, W. 2020. Degraded trees from spruce budworm epidemics as bioenergy feedstock: A profitability analysis of forest operations. *Energies* **13**(18): 4609. doi:10.3390/en13184609.
- Berger, J.-P., Leboeuf, A., Morissette, A., Daviault, B., Arsenault, M.-F., Jacques, M., Morin, J., Gagnon, J., Garceau, M.-A., Auclair, G., and D'Avignon, H. 2015. Norme de stratification écoforestière. Ministère des Forêts de la Faune et des Parcs, Direction des inventaires forestiers, Québec, Canada.
- Bonett, D.G., and Wright, T.A. 2000. Sample size requirements for estimating Pearson, Kendall and Spearman correlations. *Psychometrika* **65**(1): 23–28.
- Bouchard, M., and Pothier, D. 2008. Simulations of the effects of changes in mean fire return intervals on balsam fir abundance, and implications for spruce budworm outbreaks. *Ecol. Modell.* **218**(3): 207–218. doi:10.1016/j.ecolmodel.2008.07.001.

- Bouchard, M., and Pothier, D. 2011. Long-term influence of fire and harvesting on boreal forest age structure and forest composition in eastern Québec. *For. Ecol. Manag.* **261**(4): 811–820. doi:10.1016/j.foreco.2010.11.020.
- Bouchard, M., Pothier, D., and Gauthier, S. 2008. Fire return intervals and tree species succession in the North Shore region of eastern Quebec. *Can. J. For. Res.* **38**(6): 1621–1633. doi:10.1139/X07-201.
- Bureau de mise en marché des bois. 2019. Valeur des traitements sylvicoles non commerciaux pour l'année financière 2019-2020. Ministère des Forêts de la Faune et des Parcs, Direction des évaluations économiques et financières, Québec, Canada. [accessed 23 October 2019].
- Devine, W.D. and Harrington, C.A. 2007. Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. *Agric. For. Meteorol.* **145**(1), 125-138. doi: 10.1016/j.agrformet.2007.04.009.
- Durocher, C., Thiffault, E., Achim, A., Auty, D., and Barrette, J. 2019. Untapped volume of surplus forest growth as feedstock for bioenergy. *Biomass Bioenergy* **120**: 376–386. doi:10.1016/j.biombioe.2018.11.024.
- Dymond, C.C., Titus, B.D., Stinson, G., and Kurz, W.A. 2010. Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *For. Ecol. Manag.* **260**(2): 181–192. doi:10.1016/j.foreco.2010.04.015.
- Elbersen, H.W., Bakker, R.R.C., Harmsen, P.F.H., Vis, M., and Alakangas, E. 2015. A selection method to match biomass types with the best conversion technologies. *S2Biom.*
- Fleming, R.L., Powers, R.F., Foster, N.W., Kranabetter, J.M., Scott, D.A., Ponder Jr., F., Berch, S., Chapman, W.K., Kabzems, R.D., Ludovici, K.H., Morris, D.M., Page-Dumroese, D.S., Sanborn, P.T., Sanchez, F.G., Stone, D.M., and Tiarks, A.E. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of Long-Term Soil Productivity sites. *Can. J. For. Res.* **36**(3): 529–550. doi:10.1139/x05-271.
- Groupe DDM. 2016. Enquête 2013-2014 sur les coûts d'opération et les revenus liés au bois d'oeuvre de l'industrie forestière du Québec. Québec, Canada. [accessed 26 June 2019].
- Harrington, T.B., Slesak, R.A., and Schoenholtz, S.H. 2013. Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir. *For. Ecol. Manag.* **296**: 41-52. doi:10.1016/j.foreco.2013.01.033.
- Harrington, T.B., Peter, D.H., and Slesak, R.A. 2018. Logging debris and herbicide treatments improve growing conditions for planted Douglas-fir on a droughty forest

- 770 site invaded by Scotch broom. *For. Ecol. Manag.* **417**: 31–39.
 771 doi:10.1016/j.foreco.2018.02.042.
 772
- 773 Henneb, M., Valeria, O., Thiffault, N., Fenton, N.J., and Bergeron, Y. 2019. Effects of
 774 mechanical site preparation on microsite availability and growth of planted black
 775 spruce in Canadian paludified forests. *Forests* **10**(8): 670. doi:10.3390/f10080670.
 776
- 777 Hill, A.V. 1910. The possible effects of the aggregation of the molecules of haemoglobin
 778 on its dissociation curves. *J. physiol.* **40**: 4–7.
 779
- 780 Hins, C., Ouellet, J.-P., Dussault, C., and St-Laurent, M.-H. 2009. Habitat selection by
 781 forest-dwelling caribou in managed boreal forest of eastern Canada: Evidence of a
 782 landscape configuration effect. *For. Ecol. Manag.* **257**(2): 636–643.
 783 doi:10.1016/j.foreco.2008.09.049.
 784
- 785 Hunter, J., and Malcolm, L. 1990. *Wildlife, Forests, and Forestry. Principles of Managing*
 786 *Forests for Biological Diversity.* Prentice Hall.
 787
- 788 IPCC. 2014. *Climate change 2014: Mitigation of climate change: Working Group III*
 789 *contribution to the Fifth Assessment Report of the Intergovernmental Panel on*
 790 *Climate Change.* Cambridge University Press, New York.
 791
- 792 Iranparast Bodaghi, A., Nikooy, M., Naghdi, R., Venanzi, R., Latterini, F., Tavankar, F.,
 793 and Picchio, R. 2018. Ground-based extraction on salvage logging in two high
 794 forests: A productivity and cost analysis. *Forests* **9**(12): 729. doi:10.3390/f9120729.
 795
- 796 Kärhä, K., Anttonen, T., Poikela, A., Palander, T., Laurén, A., Peltola, H., and Nuutinen, Y.
 797 2018. Evaluation of salvage logging productivity and costs in windthrown Norway
 798 spruce-dominated forests. *Forests* **9**(5): 280. doi:10.3390/f9050280.
 799
- 800 Krankina, O.N., Harmon, M.E., and Griazkin, A.V. 1999. Nutrient stores and dynamics of
 801 woody detritus in a boreal forest: modeling potential implications at the stand level.
 802 *Can. J. For. Res.* **29**(1): 20–32. doi:10.1139/x98-162.
 803
- 804 Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth,
 805 C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J., and Apps, M.J.
 806 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change
 807 implementing IPCC standards. *Ecol. Modell.* **220**(4): 480–504.
 808 doi:10.1016/j.ecolmodel.2008.10.018.
 809
- 810 Laganière, J., Paré, D., Thiffault, E., and Bernier, P.Y. 2017. Range and uncertainties in
 811 estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced
 812 from Canadian forests. *GCB Bioenergy* **9**(2): 358–369. doi:10.1111/gcbb.12327.
 813
- 814 Méthot, S., and Auger, D. 2016. *Guide de l'évaluateur: qualité des plantations.* Ministère
 815 des Forêts de la Faune et des Parcs, Direction de l'aménagement et de
 816 l'environnement forestiers, Québec, Canada. [accessed 4 November 2018].

- Méthot, S., Blais, L., Gravel, J., Latrémouille, I., St-Pierre, S., and Vézeau, S. 2014. Guide d'inventaire et d'échantillonnage en milieu forestier. Ministère des Ressources Naturelles, Direction de l'aménagement et de l'environnement forestier, Québec, Canada.
- Ministère des Forêts de la Faune et des Parcs. 2020. Compilation des données issues des registres forestiers 2019. Présentation faite à la Table de concertation sur le marché de la matière ligneuse. Direction de la modernisation de l'industrie des produits forestiers, Gouvernement du Québec, 22 p.
- Morneau, C., and Landry, Y. 2010. Guide de reconnaissance des types écologiques de la région 6j. Ministère des Ressources Naturelles et de la Faune, Direction des inventaires forestiers, Québec, Canada. [accessed 21 November 2018].
- Morris, L.A., Pritchett, W.L., and Swindel, B.F. 1983. Displacement of nutrients into windrows during site preparation of a flatwood forest. *Soil. Sci. Soc. Am. J.* **47**(3): 591–594. doi:10.2136/sssaj1983.03615995004700030040x.
- NFI. 2010. National standards for ground plots compilation procedures. Canada's National Forest Inventory, Ottawa, Canada. [accessed 3 December 2019].
- Paré, D., Thiffault, É., Cyr, G., and Guindon, L. 2016. Quantifying forest biomass mobilisation potential in the boreal and temperate biomes. *In* Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes. *Edited by* E. Thiffault, G. Berndes, M. Junginger, J.N. Saddler, and C.T. Smith. Elsevier. pp. 36–49. doi:10.1016/B978-0-12-804514-5.00003-2.
- Peter, D.H. and Harrington, T.B. 2018. Effects of forest harvesting, logging debris, and herbicides on the composition, diversity and assembly of a western Washington, USA plant community. *For. Ecol. Manag.* **417**: 18-30. doi:10.1016/j.foreco.2018.01.045.
- Pinheiro, J., Bates, D.B., DebRoy, S., Sarkar, D., Van Willigen, B., Heisterkamp, S., and R-Core Team. 2020. nlme: Linear and Nonlinear Mixed Effects Models. Available from <https://CRAN.R-project.org/package=nlme> [accessed 16 July 2020].
- Priewasser, K., Brang, P., Bachofen, H., Bugmann, H., and Wohlgemuth, T. 2013. Impacts of salvage-logging on the status of deadwood after windthrow in Swiss forests. *Eur. J. Forest. Res.* **132**(2): 231–240. doi:10.1007/s10342-012-0670-1.
- R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from <https://cran.r-project.org/bin/windows/base/old/3.5.3/> [accessed 16 July 2020].
- Röder, M., Thiffault, E., Martínez-Alonso, C., Senez-Gagnon, F., Paradis, L., and Thornley, P. 2019. Understanding the timing and variation of greenhouse gas

- emissions of forest bioenergy systems. *Biomass Bioenergy* **121**: 99–114. doi:10.1016/j.biombioe.2018.12.019.
- Saucier, JP., Robitaille, A., and Grondin, P. 2009. Cadre bioclimatique du Québec. *In* Manuel de Foresterie, 2nd edition. *Edited by* R. Doucet, M. Côté, and Ordre des ingénieurs forestiers du Québec. Éditions MultiMondes, Québec (QC). pp. 186–205.
- She, J., Chung, W., and Han, H. 2019. Economic and environmental optimization of the forest supply chain for timber and bioenergy production from beetle-killed forests in northern Colorado. *Forests* **10**(8): 689. doi:10.3390/f10080689.
- Spaulding, P., and Hansbrough, J.R. 1944. Decay of logging slash in the Northeast. US Department of Agriculture.
- Sullivan, T.P., and Sullivan, D.S. 2014. Voles, trees, and woody debris structures as habitat: Balancing forest crop protection and biodiversity. *Crop Prot.* **60**: 70–77. doi:10.1016/j.cropro.2014.03.002.
- Thiffault, N. 2016. Short-term effects of organic matter scalping on the growth and nutrition of black spruce and jack pine seedlings planted in the boreal forest. *For. Chron.* **92**(02): 221–231. doi:10.5558/tfc2016-041.
- Timmermann, V., and Dibdiakova, J. 2014. Greenhouse gas emissions from forestry in East Norway. *Int. J. Life. Cycle. Assess.* **19**(9): 1593–1606. doi:10.1007/s11367-014-0773-7.
- Trottier-Picard, A., Thiffault, E., DesRochers, A., Paré, D., Thiffault, N., and Messier, C. 2014. Amounts of logging residues affect planting microsites: A manipulative study across northern forest ecosystems. *For. Ecol. Manag.* **312**: 203–215. doi:10.1016/j.foreco.2013.10.004.
- Ung, C.-H., Bernier, P.Y., Guo, X.J., and Lambert, M.-C. 2009. A simple growth and yield model for assessing changes in standing volume across Canada's forests. *For. Chron.* **85**(1): 57–64. doi:10.5558/tfc85057-1.
- US Department of Commerce. 2020. Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases. Available from <https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html> [accessed 20 October 2020].
- Yemshanov, D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., and Smith, S. 2014. Cost estimates of post harvest forest biomass supply for Canada. *Biomass Bioenergy* **69**: 80–94. doi:10.1016/j.biombioe.2014.07.002.

- Zenner, E.K., Fauskee, J.T., Berger, A.L., and Puettmann, K.J. 2007. Impacts of skidding traffic intensity on soil disturbance, soil recovery, and aspen regeneration in north central Minnesota. *North. J. Appl. For.* **24**(3): 177–183. doi:10.1093/njaf/24.3.177.
- Zhang, J., Young, D.H., and Luckow, K.R. 2015. Effect of redistributing windrowed topsoil on growth and development of ponderosa pine plantations. *For. Ecol. Manag.* **353**: 148–155. doi:10.1016/j.foreco.2015.05.039.

Draft

List of figures

Fig. 1. Example of a forest stand from Côte-Nord, northeastern Quebec, Canada, affected by a severe spruce budworm epidemic (photo by D. Gouge, 2019).

Fig. 2. Location of the study site and sample plots in northeastern Quebec, Canada (map from Google Earth Pro V-7.3).

Fig. 3. Representation of a sampling plot to study biomass procurement as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada. Each circular sampling plot had two orthogonal transects for coarse woody debris (CWD) and small woody debris (SWD) assessment. Circular microplots of 5 m² used for regeneration and microsite assessments are represented by red circles. A buffer of 10 m from any roads or unharvested stands was applied to avoid border effects.

Fig. 4. Site preparation costs according to a) the volume of harvested forest biomass and b) residual forest biomass as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada. Data of average harvested biomass per hectare used in panel (a) were calculated from the difference of downed woody debris mass between plots with and without biomass procurement, hence having half the data points represented in panel (b). The grey area represents the 95% confidence interval.

Fig. 5. Cumulative carbon balance for a period of 100 years for scenarios representing combinations of biomass procurement (with vs. without), regeneration methods (natural regeneration vs. site preparation and plantation) and woody debris decay rates (slow vs. medium) in northeastern Quebec, Canada. Positive values on Y axis represent greenhouse gas (GHG) emissions and negative values represent GHG sequestration. Simulations include processes on forest sites and include forest growth, debris decay and site preparation (when needed). It does not include emissions from timber harvesting and transport, and does not include energy production emissions.

Fig. 6. Cumulative carbon balance for a period of 100 years for energy production scenarios representing combinations of biomass procurement (with vs. without), regeneration methods (natural regeneration vs. site preparation and plantation), woody debris decay rate (slow vs. medium) and heat production energy systems (bioenergy from biomass vs. heavy oil) in northeastern Quebec, Canada. Positive values on Y axis represent greenhouse gas (GHG) emissions and negative values represent GHG sequestration. Simulations include processes of forest growth, debris decay, site preparation (when needed), energy production and use. It does not include emissions from timber harvesting and transport.

List of tables

Table 1. Silviculture costs used for financial analyses of biomass procurement as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada (data from regional companies and (Bureau de mise en marché des bois 2019)).

Treatment	Machinery	Cost (CAD•ha ⁻¹)
Woody debris clearance	bulldozer with rake shovel	784.00
Woody debris clearance (trail only)	bulldozer with rake shovel	196.00
Scarification	passive disc scarifier	222.00
Scarification (trail only)	passive disc scarifier	55.50
Plantation (1600 seedlings•ha ⁻¹)	NA	640.19
Trail plantation (400 seedlings•ha ⁻¹)	NA	160.05

Table 2. Forest operation data used for the financial analysis of biomass procurement as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada (data from regional companies and Groupe DDM 2016).

Data used	Average value
Transportation cost (CAD•h ⁻¹)	105.00
Loading capacity (WT•truck ⁻¹)	35
Loading cost (CAD•WT ⁻¹)	1.50
Transport distance (km)	50.5
Truck speed (km•h ⁻¹)	70
Skidding cost (CAD•ha ⁻¹)	416.82
Harvesting cost (CAD•ha ⁻¹)	1228.52

WT: Wet tonnes. CAD: Canadian dollar.

Table 3. Comparison of average regeneration and plantation microsite stocking (expressed as % of occurrence) observed in cutblocks with and without biomass procurement, as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada.

Biomass procurement	Regeneration of desired species				Regeneration or plantation	
	(minimum of 15 cm in height)	Standard deviation	Plantation microsites	Standard deviation	microsites	Standard deviation
with	74%	44%	29%	46%	83%	38%
without	59%	49%	15%	36%	64%	48%
p - value	0.030		0.046		< 0.001	
F - value	5.52		4.56		17.36	

Denominator degrees of freedom = 19 for all variables.

Table 4. Supply costs for one oven-dry metric tonne of forest biomass at the mill yard in a study investigating biomass procurement as a component of a larger forest management system that aims to provide feedstock for softwood lumber and bioenergy and ensure forest regeneration after harvesting in northeastern Quebec, Canada.

Costs	Pessimistic perspective (CAD•odmt ⁻¹)	Optimistic perspective (CAD•odmt ⁻¹)
Harvesting, collecting and forwarding to roadside	84.29	21.35
Transportation from roadside to processing plant	7.00	7.00
Total supply costs	91.29	28.35
Cost savings in site preparation and plantation	-14.45	-14.45
Total net supply costs	76.84	13.90

Note: Transport distances from roadside to processing plant is assumed to be 50 km back and forth, at an average speed of 70 km•h⁻¹, Stumpage rates have not been included in the estimation, as they are yet to be defined for the region.

996 **Appendix A. Regional standards for site preparation in Côte-Nord region**

997 Appendix A can be found online at [URL].

998

999 **Appendix B. Illustration of the scenarios and their components used for carbon**
1000 **balance analysis**

1001 Appendix B can be found online at [URL].

1002

Draft

A

B

Appendix A. Regional standards for site preparation in Côte-Nord region

- NO TREATMENT :
- Thin soil ≤ 15 cm;
 - Stocking $> 60\%$ of viable regeneration of desired species with an height ≥ 15 cm;
 - Stump stocking 10% superior to desired regeneration stocking (removed criteria for intensive management);
 - Wetland;
 - Slope $> 40\%$.
- TRAIL TREATMENT ONLY :
- 40 % to 60 % of desired regeneration with an height ≥ 15 cm
- REVISION REQUIRED :
- More than 40 % of desired regeneration with an height < 15 cm.
- DIRECT PLANTATION :
- Low woody debris and humus < 5 cm.
- SIMPLE SCARIFICATION :
- Low woody debris and humus < 25 cm;
 - Slope $< 25\%$.
- WOODY DEBRIS CLEARANCE ONLY :
- Medium woody debris and humus < 15 cm;
 - Slope $< 25\%$.
- DOUBLE SCARIFICATION :
- Medium woody debris, humus < 25 cm or low woody debris, humus > 25 cm;
 - Slope $< 25\%$.
- WOODY DEBRIS CLEARANCE + SCARIFICATION :
- High woody debris, humus > 15 cm or medium woody debris, humus > 25 cm;
 - Slope $< 25\%$.
 - Cutblock with difficult trafficability;

HYDRAULIC EXCAVATOR :

- Slope > 25 %.

HARVESTER :

- More than 10 commercial trees within the sample plot of 11.28 m radius.

SOFTWOOD COARSE DEBRIS CLASSES :

- Low: 0 to 10
- Medium : 11 to 25
- High : 26 and more

HARDWOOD COARSE DEBRIS CLASSES :

- Low: 0 to 5
- Medium : 6 to 20
- High : 21 and more

Plantation is done after site preparation treatments. For trail treatments, trees are planted only on the trail area.

Standards are based on data and guidelines from regional companies.

Appendix B. Illustration of the scenarios and their components used for carbon balance analysis.