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A financial analysis of the potential of dead trees from the boreal forest of eastern Canada to serve as feedstock for wood pellet export

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HIGHLIGHTS

- The spruce budworm outbreak will increase the amount of dead trees in Eastern Canada.
- Wood degradation did not affect the eligibility of dead trees for pellet production.
- Lumber and pulp production remains the most profitable option except in small trees.
- A drop by 20–40% in wood chip price would make pellet and pulp scenarios equivalent.

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ABSTRACT

Global demand for forest biomass feedstock has increased drastically in recent years, mainly due to the implementation of policies and strategies for climate change mitigation and renewable energy production in many jurisdictions. The biomass from dead trees has been recognized by the International Panel on Climate Change (IPCC) as a promising source of forest biomass for bioenergy at the global scale both because of its wide scale availability and its potential to limit global warming. In eastern Canada, dead trees are not only very abundant but are also widely perceived by lumber and pulp and paper producers as contaminants in the wood supply chain with marginal profitability. The general aim of this study was to determine the conditions of profitability of an eastern Canada independent sawmill (*i.e.*, unaffiliated with a pulp plant) to produce pellets destined for international export using either co-products or roundwood from dead trees as feedstock. We compared the yield and monetary value of dead trees at various sizes and degradation levels for the production of wood pellets, alone or in conjunction with the production of lumber, to current market conditions. Our results suggest that using dead trees for lumber and pellets is almost as profitable as using them for lumber and pulp, with a difference of about 1–12% depending on tree size. Dead trees from all classes of wood degradation could serve as an interesting feedstock for pellets because wood density was only slightly affected by wood degradation. Small dead trees (DBH < 15 cm) could serve for all scenarios, as the difference between revenues and costs remained generally minimal between them. Larger dead trees did not appear to represent a financially viable option under current market prices, unless suitable subsidies or other types of financial support are provided. The sustainability criteria applied by European consumers could therefore be a determining factor for the future importance of dead trees from eastern Canada as a source of feedstock for wood pellet production.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) [1], the International Energy Agency [2] and the International Renewable Energy Agency [3] have all identified forest biomass as an important source of energy to meet future requirements both in terms

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of future energy consumption and reduction of GHG emissions. When suitably used, forest biomass will lead over time to a net reduction in greenhouse gas (GHG) emissions when used as a substitute for fossil fuels [4–9]. In many jurisdictions, renewable energy policies and strategies have recently been implemented, leading to an increase demand for forest biomass at the global scale [10].

In Europe, the European Union (EU) member states have agreed on a 2030 Framework for climate and energy that states that by 2030, at least 27% of the total energy consumption should be supplied by renewable energy resources [11], the wood pellet demand is expected to continue to increase. Although a majority of the wood pellet demand in the EU has been supplied domestically, international trade also plays an important role, which is likely to increase in the future [12] and some EU countries such as the UK and the Netherlands have become increasingly reliant on international imports [13,14]. For the past 10 years, Canada has been a major overseas supplier of pellets to Europe [15,16] with the pellets mostly coming from British Columbia (BC). In this province, the mountain pine beetle outbreak killed large volumes of pine stands over the last number of years and has prompted a significant increase in harvest levels. This situation stimulated the development of BC's wood pellet production and export capacity by increasing feedstock availability in the form of sawmill residues, tree parts, and whole trees [17]. In 2015, BC exported 1 258 902 tonnes of wood pellets, 81% of which were sent to the UK [16]. The production of wood pellets in Canada's eastern provinces is still rather limited and mainly focused on domestic markets, despite proximity to deep-sea ports and shorter maritime routes to Europe. Wood pellet producers from Quebec exported only 138 945 tonnes of their production, which was almost entirely sent to the United States [16].

The boreal forests of eastern Canada contain an abundance of dead trees, which were either killed by natural disturbances (fire, insect outbreaks), or died through the course of stand succession. This type of biomass has been recognized by the IPCC [1] and by assessments made in various jurisdictions *e.g.* [18,19] as a promising source of feedstock for bioenergy. In European countries such as Italy [20], Finland and Sweden [21], frequent thinnings throughout the course of stand succession provide feedstock for bioenergy in the form of small or damaged/dying whole trees. Although this limits the occurrence of interspersed dead trees at the end of succession, large amounts of dead tree biomass may become available following major disturbance events such as windthrows, wildfires and insect outbreaks. Such natural disturbances are becoming more frequent at the global scale [22–24].

The most destructive insect in eastern Canada is the spruce budworm (*Choristoneura fumiferana* (Clemens)), which has outbreak cycles of 30 to 40 years. It mainly affects balsam fir (*Abies balsamea* (L) Mill.) and white spruce (*Picea glauca* (Moench) Voss) [25–28]. Because of warmer average temperatures resulting from climate change, the insect is moving further north, attacking forests and tree species that had remained relatively unaffected in the past such as black spruce (*Picea mariana* Mill. BSP)[29]. The current spruce budworm outbreak is expected to cause severe damage to the forest resource. In the province of Quebec alone, more than 7 million hectares have been affected since the beginning of the infestation in 2006 [30]. During the last spruce budworm outbreak, which occured in the 1970 s, the insect killed from 139 000 000 to 238 000 000 m^3 of balsam fir and spruce in the public forests of eastern Canada [31]. The outbreak caused severe damage to both lumber and pulp and paper industries *e.g.* [32–34].

Dead trees can also be found sporadically *(i.e.,* interspersed within stands) in undisturbed stands of eastern Canadian forests. In regions bordering the Atlantic ocean or the St.Lawrence Estuary, the maritime climate can induce mean fire return intervals of more than 300 years, which is much longer than the approximate 100-year intervals reported further inland [35]. In the absence of insect outbreaks, this implies that the period of time since the last major disturbance often exceeds the mean longevity of the trees. Isolated mortality therefore generates significant volumes of standing dead trees interspersed with live trees [36]: for example, in Quebec's North Shore region, dead wood can typically represent about 22% of the total volume in old stands [37].

In eastern Canada, harvesting of interspersed dead trees usually occur as part of normal harvesting operations. In the case of stands affected by natural disturbances, this is performed as part of emergency salvage harvesting plans. However, dead trees are widely recognized by lumber and pulp and paper producers to be of low quality and marginally profitable, and are thus often seen as "contaminants" in the wood supply chain [38]. On the other hand, the calorific value of wood from dead trees is not significantly affected by decay [39]. Dead trees could therefore be considered an interesting feedstock for the production of energy products such as wood pellets [40].

Despite the significant feedstock availability in the boreal forests of eastern Canada and recent advances in the development of solid, liquid and gaseous biofuels and bioproducts, the long-term prospects of using wood in a bio-based economy are not fully recognized by local stakeholders, which makes it difficult to mobilize support for improvement of logistics [41]. To make the most of the opportunity offered by international trade flows of biomass and global bioenergy systems, Canada's forest sector is currently considering strategies for increasing the mobilization of its forest biomass supply chains [42]. Increasing knowledge of the economics of pellet supply chains using various potential sources of feedstock, and their integration within the forest value chain along with conventional wood products, is therefore crucial to aid policy-makers and stakeholders.

In the province of Quebec, sawmills represent the main entry point of the forest value chain. Conifer roundwood of all dimensions harvested on public lands is first transported to sawmills. Sufficiently large roundwood is normally sawn for dimensional lumber, while slabs and small-size roundwood are chipped on site. Lumber processing creates co-products in the form of sawdust, shavings and wood chips, which the mill can sell as feedstock to a pulp plant or a pellet mill [43]. Revenues from such co-products are an integral part of the sawmill profitability. For some pulp plants, the low quality of co-products from dead roundwood disqualifies them for pulp production [44], which can make the production of wood pellets a preferable processing pathway. The downturn of the global paper markets may also mean that there are no takers for sawmill co-products, representing an opportunity to develop the pellet market.

Exploring various ways in which dead trees can serve as ecologically sustainable feedstock for forest value chains in Canada, including energy products such as wood pellets, would open new opportunities of value creation for the forest sector [45]and contribute to meeting the renewable energy demand at a global scale [14,46]. This could also provide a case-study example of how the forest sector in Canada and in other countries can adapt to the predicted increase in natural disturbances.

The general aim of this study was to determine the conditions of profitability for an eastern Canada independent sawmill in producing pellets destined for international export using either co-products or roundwood from dead trees as feedstock. Specifically, we estimated the yield and monetary value of dead trees of various sizes and degradation levels for the production of wood pellets, alone or in conjunction with the production of lumber. We then compared these to the reference system, *i.e.*, current market conditions where lumber and pulp are the main products from the forest sector.

2. Material and methods

2.1. Field sampling (study sites)

Four different production scenarios, with varied product assortments were simulated at the tree level. To do this, we referred to previous studies by Barrette et al. [37,38,44] on wood properties and lumber production from interspersed dead trees. Combining these with new data on wood density and moisture content from trees killed by the current spruce budworm outbreak [47], we assessed the effects of degradation on the monetary value of trees. Value was evaluated as perceived by a sawmill, *i.e.*, by considering the value of lumber, chips, shavings and sawdust as potential sources of income. In addition to the tree level analysis, we simulated four different harvesting scenarios at the stand level, using inventory data from Barrette et al. [37] on interspersed dead trees and inventory data from Bognounou et al. [47] on spruce budworm-killed trees. A sensitivity analysis was performed to determine to what extent a change in the value of wood chips for pulp could affect the comparison with a scenario involving the production of wood pellets.

All data sets used for this study were collected in the North-Shore region of Quebec, Canada. These forests are part of the boreal biome and are largely composed of old stands vulnerable to spruce budworm outbreaks. Because of the long fire return interval in this region [35], many forests contain a large number of dead trees [37].

2.2. Sample trees and collection of wooden discs

2.2.1. Trial 1: Dead trees interspersed within stands

In the previous studies by Barrette et al. [38,44] a sawmill conversion analysis was carried out to compare visual lumber grades and value yield from live and dead merchantable black spruce trees in three different states of wood decomposition. These studies provided the basis to assess and compare the yield and monetary value of dead trees of various sizes and degradation levels for the production of wood pellets - alone or in conjunction with the production of lumber - relative to the reference system of lumber and/or pulp production. Barrette et al. [38,44] selected sample trees according to the classification system proposed by Hunter [48] of the progressive stages of tree decomposition. The following Hunter classes were considered for production purposes: 1) live trees, 2) live but declining trees (with Hunter 1&2 being regrouped into one ‘live tree’ category), 3) recently dead trees, and 4) dead trees with loose bark. Within each group, sample trees were selected from three merchantable DBH classes (diameter at breast height 1.3 m above the ground level), *i.e.*, 9.1 to 15 cm, 15.1 to 21 cm, and >21.1 cm. Six trees were sampled in each combination of DBH and Hunter class at each of three sites. All trees were cut into logs and sawn at a modern sawmill (Boisaco, Sacré-Coeur, QC). Overall, 822 pieces of lumber were produced, and were then graded green and dry by a qualified inspector in accordance with the National Lumber Grades Authority (NLGA) Standard Grading Rules [49]. This made it possible to assess the lumber recovery of trees of different sizes and degradation levels. Wooden discs were collected at a height of 5 m along the tree stem; it was not possible to collect samples at a lower height because 16 ft. long (or 4.88 m) logs were required for lumber production in the studies by Barrette et al. [38,44].

2.2.2. Trial 2: Dead trees from stands attacked by spruce budworm

In the fall of 2013, 49 live and dead balsam fir and black spruce trees from three study sites used by Bognounou et al. [47] were harvested to assess the impact of spruce budworm on wood degradation. The samples covered the same four Hunter classes as in Trial 1, and aimed to represent the average DBH of the trees at each site. Wood density measurements were required to turn tree volume into tree mass for pulp or wood pellet production. Wooden discs of about 2.5 cm in thickness were collected at DBH (1.3 m high).

In both trials, collected wooden discs were kept in sealed plastic bags to retain their humidity. They were then brought back to the laboratory and stored in a freezer at −5 °C.

2.3. Sample preparation for laboratory analysis

2.3.1. Wood density measurements

Wood density was measured on disc samples from both trials. Before making measurements, the bark was removed. The volume of the disc sections from both trials was measured in water-saturated conditions following ASTM standard D 2395-07 [50]. The samples were then oven-dried for 24–27 h at 102.5 ± 2 °C and wood density (WD or specific gravity) was calculated using Eq. (1).

$$WD = \frac{dry\ mass\ (\mathrm{g})}{wet\ volume\ (\mathrm{cm}^3)} \tag{1}$$

2.3.2. Moisture content measurements

Sections of wooden discs from trial 2 (measurements had not been made in trial 1) were used to measure moisture content on a dry and wet basis for the two tree species sampled (balsam fir and black spruce) and four different stages of wood decomposition (Hunter 1 to Hunter 4). Before making measurements, the bark was removed. The green mass of each section was first measured, and then samples were oven-dried at 102.5 ± 2.5 °C for 24 h and weighed to obtain their dry mass following ASTM standard D 4442-07 [51]. Moisture content was derived using Eqs. (2) and (3), both on a dry and wet basis.

$$MC\ dry\ basis = \frac{Mh - Mo}{Mo} * 100 \tag{2}$$

$$MC\ wet\ basis = \frac{Mh - Mo}{Mh} * 100 \tag{3}$$

where Mh represents the green mass of the wooden disc section (g) and Mo the oven-dried mass (g). Sample discs were weighed to the nearest 0.01 g. Both types of moisture content (MC) were determined to provide estimates of material flow after tree death. Both sawmills and wood pellet factories tend to use MC on a dry basis, whereas the pulp and paper sector uses MC on a wet basis.

2.4. Data analysis

2.4.1. Wood density and moisture content statistical analysis

Tests of the statistical significance of the differences observed among Hunter classes (*i.e.*, wood degradation levels) and tree species' wood density (wet basis) and moisture content (wet and dry basis) were made using linear models [52]. The interaction between species and Hunter class was examined using both wood density and moisture content. Only significant terms or interactions were kept in the analysis (using a p-value < 0.05) [53].

2.4.2. Utilization scenarios for dead trees

To determine the monetary value and profitability associated with the utilization of dead wood, four different scenarios were investigated, which varied according to the assortment of wood products (Fig. 1). To make scenarios as comparable as possible, costs and revenues were calculated from the point of view of a sawmill acquiring and processing a load of roundwood.

The reference scenario, i.e. the current market scenario in eastern Canada (Scenario 1), was defined as a situation in which a sawmill buys a supply of roundwood including dead trees for lumber production and then sells its co-products (sawdust, shavings and wood chips) to a neighboring (unaffiliated) pulp plant [43]. Costs were therefore calculated as the sum of the costs of roundwood supply and lumber production, and revenues were calculated as the sum of revenues from lumber and the sale of co-products to pulp plants using average data for 2014 [54].

In alternative scenarios, a sawmill is also assumed to buy a supply of roundwood containing dead trees. In Scenario 2, dead trees are processed at the sawmill and all of the co-products are utilized by its own pellet mill. The potential profits associated with pellet production were estimated as the difference between the costs of pellet production and revenues from pellets sold to international markets in Europe using free on board (FOB) prices for Canada in 2014 [55].

In Scenario 3, dead trees are processed into wood chips at the sawmill and sold to a neighboring (*i.e.*, unaffiliated) pulp plant. In Scenario 4, dead trees are ground and pelletized by the sawmill's pellet mill and sold to Europe. Therefore, costs included roundwood supply costs as in Scenarios 1 and 2 for dead trees. In Scenario 3, additional costs were associated with the cost of chipping, while revenues were associated with the sale of wood chips to a neighboring pulp plant. In Scenario 4, additional costs were associated with the production and transport of wood pellets, while the estimated revenues were calculated based on the value of the pellets on the European market.

Scenario 2 is plausible in a context in which degraded dead wood is often considered as a contaminant in the supply of wood chips for pulp [40]. Scenarios 3 and 4 represent alternative scenarios for situations in which the supply of roundwood from dead wood is deemed to be of insufficient quality to produce lumber; whole trees are therefore directed to pulp or wood pellet production. On the one hand, several sawmills in eastern Canada are affiliated with pulp plants, which creates a direct pathway for the supply of wood chips. On the other hand, some independent sawmills are unaffiliated and now equipped to produce their own pellets on-site. The different scenarios were tested for both black spruce and balsam fir based on various sizes and degradation levels (Hunter classes). All revenues and costs for each scenario are provided in Tables 1 and 2.

Table 1
Revenues.

Abbreviation	Description
L	Lumber revenues vary according to board size and quality. They were determined using Random Lenghts' Yardstick (2014 Annual Price Averages Special Report)
Sa	Sawdust and shaving revenues were determined from personal communication in 2015; we used and average of 55 USD/odt
Wc	Wood chips revenues were determined based on Random Lengths' Yardstick for eastern Canada wood chips (December 2014); we used an average of 100 USD/odt
Wpi	Industrial wood pellet revenues (Wpi) for exportation to Rotterdam were based on Argus Biomass Markets (Issue 14-030, Wednesday 30 July 2014) We used an average of 160 USD/t (fob for southwestern Canada since there are no fob for eastern Canada)

2.4.2.1. Feedstock supply costs (used in all scenarios). Tree feedstock supply cost was estimated by adding the stumpage fee to transport and felling costs. These costs were calculated on a cubic metre basis, but were scaled to the tree level in the results. The stumpage cost was provided by the 'Bureau de mise en marché des bois du Québec' (BMMB) [56] for public forests of the North-Shore region in 2014. The BMMB provides stumpage costs for both live and dead trees. Stumpage costs for live trees are divided into two quality classes: lumber and pulp. For dead trees, only one stumpage cost is used. Transport cost was obtained from a confidential report (2013), while felling costs were simulated using FPInterface Express [57] software for conifers of various sizes. The software uses mean cost statistics to make simple estimates of productivity and cost for various harvesting systems. Input data for the simulation were based on forest inventory data at the stand level (merchantable volume in m^3/ha, average tree DBH and average tree merchantable volume) taken from Barrette et al. [37]. Our simulations were based on typical machinery used in the North-Shore region (*i.e.*, grapple harvester and carrier). Transport and felling costs were adjusted for 2014 prices using inflation values and then converted into US dollars (USD) using conversion rates from the Bank of Canada website [58]. Details of the feedstock supply costs included in each scenario are provided in Table 2. Based on knowledge currently available, it was assumed that harvesting logistics and costs were unaffected by tree degradation levels [59].

2.4.2.2. Production of lumber and co-products. Simulations of lumber recovery in balsam fir and black spruce in Scenario 1 and 2 were made using StatSAW [60], a statistical model that predicts the lumber products assortment (expressed as the sum of board feet per lumber dimension class) for a tree of a given DBH and height. Adjustments to StatSAW predictions on trees from Hunter 3 and

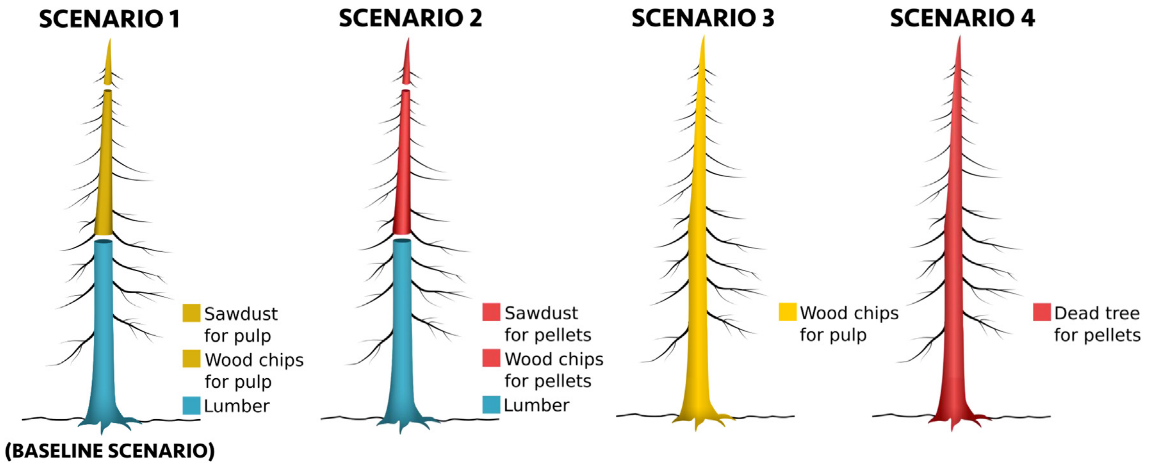

Fig. 1. Dead tree utilization scenarios.

Table 2
Costs.

Abbreviation	Description	Costs 2014	Units	Reference
D	Delivery costs of lumber	62.70	USD/TBF	Personal communication in 2015[a]
Da	Transportation cost by truck (in bulk) from the wood pellet mill to the port in Port-Cartier (Quebec, Canada)	10.30	USD/t	Adapted from Arsenault and Roy (2013),[b] p. 55; 2.40 CAD/km
Dr	Transportation cost by ship (in bulk) from Port-Cartier (Quebec, Canada) to Rotterdam (the Netherlands)	57	USD/t	Adapted from Arsenault and Roy (2013), p. 65
Dry	Drying of the raw material	14	USD/t	Personal communication in 2015
F	Felling	Varies with tree size	USD/m^3	FPInterface Express (2010)[c]
G	Grinding of dead trees	16	USD/t	Personal communication in 2015
Sc	Lumber production, drying and planing	Varies with tree size	USD/TBF	Adapted from a confidential report (2013)[d]
Sd	Stumpage (quality pulp - living or dead tree)	6.70	USD/m^3	BMMB (2014)[e]
Sl	Stumpage (quality lumber - living tree only)	14.90	USD/m^3	BMMB (2014)[f]
T	Transport	25.40	USD/m^3	Based on a confidential report (2013)[c]
Wcc	Chipping of dead trees with debarking	40	USD/t	Personal communication in 2015
Wpc	Wood pellet processing operations	41	USD/t	Personal communication in 2015
Wpdc	Wood pellet production cost (including drying cost)	55	USD/t	Personal communication in 2015

[a] Delivery costs were based on a transport distance of about 1000 km. A loaded truck can deliver about 50 TBF. Costs were converted into USD using: http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de–devises-dix-dernieres-annees/.

[b] Delivery costs were based on a transport distance of about 170 km. A loaded truck can deliver about 39 tonnes. Costs were converted into USD using: http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de–devises-dix-dernieres-annees/ and adjusted for 2014 prices using inflation calculator at http://www.usinflationcalculator.com.

[c] Adjusted for 2014 prices using inflation at http://www.bankofcanada.ca/rates/related/inflation-calculator/ and converted into USD using: http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de–devises-dix-dernieres-annees/.

[d] Adjusted for tree size on the basis that sawmill costs are equivalent to 140 CAD/TBF. Adjusted for 2014 prices using inflation at http://www.bankofcanada.ca/rates/related/inflation-calculator/ and converted into USD using: http://www.banqueducanada.ca/taux/taux-de-change/convertisseur-de-devises-dix-dernieres-annees/.

[e] Tarification zone: Baie-Comeau 960. Quality pulp stumpage refers to the volume of living trees comprised between 13 cm in diameter and 9 cm in diameter. Dead stumpage was applied to all dead trees.

[f] Tarification zone: Baie-Comeau 960. Refers to the volume of living trees comprised between the bottom of the tree up to 13 cm in diameter.

4 categories were made to account for the effect of wood degradation on lumber production, which results from an increased presence of decay and of broken tree tops [38]. Using the lm library in R, a statistical model was fitted to the raw data from the study by Barrette et al. [38] to predict the ratio of lumber volume obtained from dead trees (Hunter 3 and Hunter 4) to that of live trees of similar DBH. The ratio was then applied to the StatSAW predictions to obtain lumber yield values for both Hunter 3 and 4 dead trees (refer to Table A1 and Fig. A1 in the Appendix for further details).

For a given DBH, total tree height was estimated using the equations provided in Auty et al. [60]. The merchantable volume (tree top diameter = 9 cm), sawing volume (tree top diameter = 7 cm) and total stem volume (in m^3) were calculated by integrating the inside-bark taper models developed by Li et al. [61] for balsam fir and black spruce. Similar to what was done for lumber, a second set of ratios was calculated from the study by Barrette et al. [38] to account for the reduction in stem volume in dead trees (refer to Table A2 and Fig. A2 in the Appendix for further details). The distribution of NLGA lumber grades was estimated for each Hunter class using the same proportions as those obtained in Barrette et al. [38].

The volume of lumber residues (*i.e.*, co-products) was then estimated by subtracting the estimated volume of freshly-cut lumber from the estimated stem volume (1000 board feet = 2.36 m^3). It was also estimated that 6% of the log volume was converted into sawdust and shavings [62]. The remaining volume of solid wood contained in a tree was also assumed to be available in the form of wood chips for the production of pulp (Scenario 1) or pellets (Scenario 2). The volumes of wood chips, sawdust and shavings were turned into oven-dry masses by multiplying them by the wood density values obtained from the previously described datasets.

2.4.2.3. Lumber production costs and revenues (used in Scenarios 1 and 2). Lumber production costs included three main components: lumber production, drying and planing. The total average cost of these three steps was estimated at CAN$ 140 per thousand board feet (TBF) (Tables 1 and 2) (Confidential report 2013). An adjustment was made to include the effect of tree size, since it is an important limiting factor for profitability in the boreal forest of eastern Canada. We multiplied the cost of CAN$140 by the ratio of TBF per m^3 predicted by StatSAW for the average tree size in the forest inventory of [37]. This provided an average processing cost per unit volume (m^3) of roundwood. By associating the processing cost of a log to its size, we avoid an artificial reduction of production costs for dead trees that tend to produce less lumber per unit volume of roundwood because of an increased presence of defects. Lumber production costs were also adjusted for 2014 prices converted into USD using the same procedure as described above. The delivery cost of lumber to the retailers was based on personal communication with sawmill owners and was estimated at CAN$69 per TBF for a haulage distance of about 1000 km. Again, the delivery cost was converted to USD. Table 2 provides additional details on the lumber production costs.

The monetary value of lumber for a given tree was ultimately obtained by calculating the sum of all lumber products (dimensions and NLGA grade) multiplied by their respective values. The latter were obtained by using an average annual price index for the year 2014 for lumber sold to the Great Lakes market (Table 1) [54].

2.4.2.4. Wood chips for pulp production (used in Scenarios 1 and 3). The value of wood chips was calculated using the 2014 average annual price index for North American Conifer Chip Prices in eastern Canada and was estimated at 100 USD/oven-dry tonne (ODT) [54]. The value of sawdust and shavings was estimated using information obtained through personal communications with sawmill owners in Quebec and was estimated at 55 USD/ODT.

For Scenario 3, the cost of producing wood chips from whole dead trees was also evaluated through personal communications with pulp mill producers. Processing steps included chipping and debarking costs. The cost of debarking and chipping was estimated at 40 USD/ODT. No delivery costs were included in scenario 3 as this scenario is mostly plausible in the previously described case where the sawmill and pulp mill are located on the same site. Table 2 provides additional information on wood chipping costs.

2.4.2.5. Pellets (used in Scenarios 2 and 4). For the production of wood pellets, we applied a conversion factor to estimate the mass of wood pellets that could be produced from the estimated volumes of co-products (sawdust, shavings and wood chips; Scenario 2) or whole trees (Scenario 4). We used a conversion factor of 1.37 tonne of feedstock (MC around 10% - dry basis) per tonne of wood pellets. This was obtained from pellet producers in Quebec who use balsam fir and black spruce as their main source of feedstock (QWEB, unpublished data). The value of wood pellets for the industrial market in Europe was estimated at 160 USD/tonne (t) using Argus Biomass Markets' free on board prices (FOB) for southwest Canada in 2014 [55](as no FOB prices are not yet available for eastern Canada) (Table 1).

In Scenario 2, the raw material was assumed to be sourced from co-products at the sawmill after lumber production. Accordingly, we considered only the additional costs of production processing (drying, grinding and pelletizing) and of pellet delivery to Rotterdam harbor in the Netherlands. The cost of producing wood pellets from lumber co-products was thus estimated at 55 USD/ODT (personal communications with wood pellet producers). The pellet processing facility was assumed to be located on the same site as the sawmill. Therefore, no delivery cost of wood chips was included in the calculations.

In Scenario 4, the raw material used in the production of wood pellets was ground dead trees. Therefore, the production cost included the cost of grinding dead trees, drying and pelletizing. A cost of 71 USD/t was estimated according to personal communications with wood pellet producers that had previously used dead trees as feedstock. For both Scenarios 2 and 4, transport cost by truck from the pellet mill to Port-Cartier harbor (North Shore region of Quebec) as well as the shipping cost from Port-Cartier to Rotterdam harbor were obtained from Arsenault and Roy [63] (0.06 USD/t/km, 52 USD/t). Both transport costs were converted into USD using the Bank of Canada website [58] and adjusted for 2014 prices using an USD inflation calculator [64]. Shipping costs from Port-Cartier to Rotterdam include the costs for first handling, wharfage, inspection fees, ocean-going ship and unloading at the Rotterdam harbor. Tables 1 and 2 provide additional information on the revenues and costs associated with wood pellet production.

2.4.3. Differences between revenues and costs at the tree level

The differences between revenues and costs were reported at the tree level for black spruce and balsam fir of different sizes and degradation levels. All revenues and costs were adjusted to 2014 prices and expressed in US dollars. These are presented in Tables 1 and 2, respectively. Transport distances are also provided in Table 2. Eqs. (4)–(7) summarise the revenues and costs included in each scenario, where revenues are represented by L = lumber, Sa = sawdust and shaving, W*c* = wood chips and Wpi = industrial wood pellets. Costs are represented by: D = delivery of lumber, Da = wood pellet transport by truck from the pellet mill to Port-Cartier harbor (Quebec, Canada), Dr = wood pellet shipping cost from Port-Cartier to Rotterdam harbor (The Netherlands), Dry = drying cost, F = felling cost, G = grinding cost, Sc = lumber production cost, Sd = stumpage cost of dead trees or live tree ('pulp' quality), Sl = stumpage cost of live trees ('lumber' quality), T = transport cost, Wcc = chipping with debarking cost, Wpc = wood pellet processing operation cost, Wpdc = wood pellet production cost. Eqs. (4a) and (4b) were used in Scenario 1 to evaluate the difference between revenues and costs for an eastern Canadian sawmill processing dead and live trees for the production of conventional products (a) live tree and (b) dead tree. Eq. (5) was used in Scenario 2 to evaluate the difference between revenues and costs for an eastern Canadian sawmill processing dead trees to produce lumber and pellets. Eq. (6) was used in Scenario 3 to evaluate the difference between revenues and costs for an eastern Canadian sawmill chipping dead trees for a neighboring pulp plant. Eq. (7) was used in Scenario 4 to evaluate the difference between revenues and costs for an eastern Canadian sawmill's pellet mill grinding dead trees for pellet production. The abbreviations used in the equations are further explained in Tables 1 and 2.

$$Diff_{scenario1\ (Live\ tree)} = (L + \mathrm{Wc} + \mathrm{Sa}) - [(\mathrm{Sl} + \mathrm{Sd}) + \mathrm{T} + \mathrm{F}) + (\mathrm{Sc} + \mathrm{D})] \tag{4a}$$

$$Diff_{scenario1(Dead\ tree)} = (\mathrm{L} + \mathrm{Wc} + \mathrm{Sa}) - [(\mathrm{Sd} + \mathrm{T} + \mathrm{F}) + (\mathrm{Sc} + \mathrm{D})] \tag{4b}$$

$$\begin{aligned} Diff_{scenario2\ (Dead\ tree)} = {} & (\mathrm{L} + \mathrm{Wpi}) - [(\mathrm{Sd} + \mathrm{T} + \mathrm{F}) + (\mathrm{Sc} + \mathrm{D}) \\ & + (\mathrm{Wpdc}) + (\mathrm{Da} + \mathrm{Dr})] \end{aligned} \tag{5}$$

$$Diff_{scenario3\ (Dead\ tree)} = (\mathrm{Wc}) - [(\mathrm{Sd} + \mathrm{T} + \mathrm{F}) + (\mathrm{Wcc})] \tag{6}$$

$$\begin{aligned} Diff_{scenario4\ (Dead\ tree)} = {} & (\mathrm{Wpi}) - [(Sd + \mathrm{T} + \mathrm{F}) + (\mathrm{G} + \mathrm{Dry} + \mathrm{Wpc}) \\ & + (\mathrm{Da} + \mathrm{Dr})] \end{aligned} \tag{7}$$

2.4.4. Utilization scenarios at the stand level

Using inventory data from a post-fire chronosequence with varying levels of interspersed dead trees [37] and from stands affected by the most recent spruce budworm outbreak [47], different harvesting operations were simulated at the stand level. Simulations were made for different times since the last fire and since the start of an insect outbreak. The forest stands used for these simulations were selected to represent an average stand at each time since the disturbance. In the case of the post-fire chronosequence, four separate stands were used, while repeated measurements of the same stand were used in the post-budworm scenario. Using tree values estimated for a given scenario of utilization, tree species, size and degradation level, the information could be scaled up from the tree- to the stand level. In all simulations, live trees were assumed to be harvested for the production of conventional products (Scenario 1). Dead trees (Hunter classes 3 & 4) were harvested according to any one of the scenarios in four different stand-level simulations (Fig. 2).

2.4.5. Sensitivity analysis

A sensitivity analysis was performed to determine the effect of the wood chip value on the comparison between Scenarios 3 and 4. The wood chip price was decreased by 20% and 40%, successively, compared to the value initially used in the analysis (*i.e.*, 100 USD/ODT; Table 1).

3. Results

3.1. Wood density and moisture content

Results of the statistical tests showed that balsam fir had significantly lower wood density than black spruce, and that there was a small but significant decline in density in Hunter classes 3 and 4 classes compared to live trees. The mean density of black spruce varied from 0.41 to 0.44 g/cm^3, whereas the mean density of balsam fir varied from 0.33 to 0.36 g/cm^3 (Table 3; Fig. 3) between the different Hunter classes.

Balsam fir had significantly higher MC values compared to black spruce. However, samples of their dead tree categories (Hunter 3 and Hunter 4) had significantly lower MC than their live tree (Hunter 1) counterparts (Table 4; Fig. 4). The average MC (dry basis) of black spruce varied between 72 and 34% in Hunter classes 1 and 4,

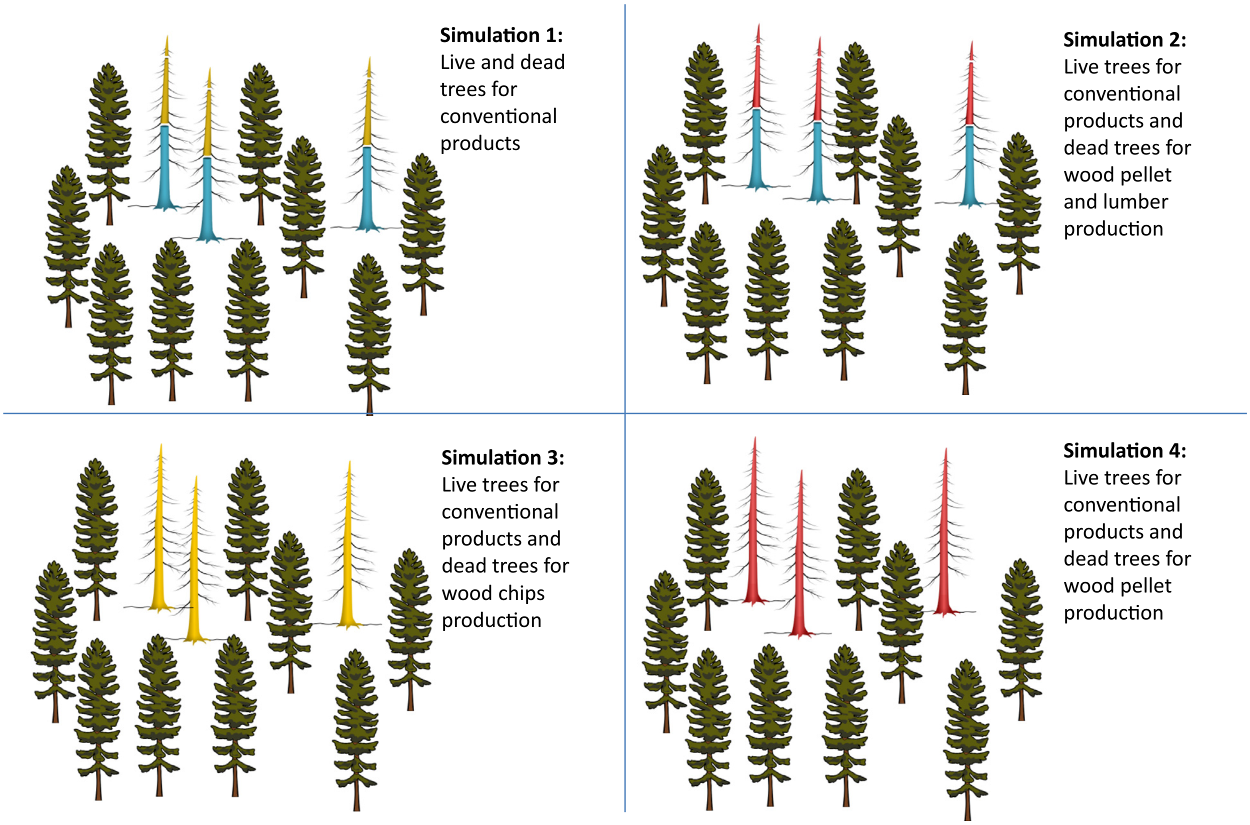

Fig. 2. Illustration of the simulations made at the stand level.

respectively. In balsam fir the same Hunter classes had MC values of 104 and 67%, respectively (Fig. 4).

3.2. Simulations of scenarios tested at the tree level

Results of the different scenarios tested at the tree level showed that processing dead balsam fir and black spruce trees for the production and exportation of wood pellets to Europe or for the production of wood chips for pulp, alone or in conjunction with the production of lumber, could hardly generate any new profits for a sawmill (Figs. 6 and 7). An examination of the reference scenario tested (Scenario 1) revealed that live trees offer much better financial profitability than dead trees. There was a large financial gap between live and dead trees, especially for Hunter class 4 trees, which provided the lowest financial yield (Fig. 5). In all cases, Scenarios 1 and 2 showed higher profitability than Scenarios 3 and 4, suggesting that lumber production is essential to limit losses from dead trees, especially in trees with DBH larger than 20 cm.

For dead trees, the difference in profitability was not large between Scenarios 1 and 2 (production of lumber and co-products for wood pellets), especially in trees with DBH smaller than 15 cm (Fig. 6). In balsam fir, the difference between Scenarios 1 and 2 remained almost constant for the different tree sizes rep-

Table 3
Fixed parameters, estimates, associated standard errors and p-values of the fixed effects estimates for the linear mixed models describing the relationship between wood density (wet basis) and tree species for the different levels of wood decomposition.

	Estimates	Std. error	P-value
Hunter 1 (Living)	0.43	0.005	<0.001
Hunter 2 (Living but declining)	−0.01	0.012	0.34
Hunter 3 (DSW)	−0.02	31.9	0.002
Hunter 4 (DSW)	−0.015	0.006	0.02
Species (BF)	−0.07	0.008	<0.001

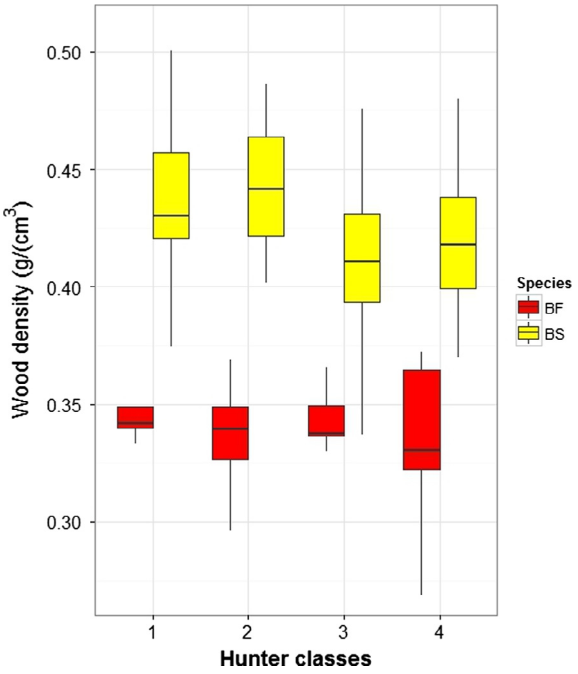

Fig. 3. Boxplot of wood density value (g/cm^3) according to species and Hunter classes (Hunter 1 and 2 = live trees, Hunter 3 and 4 = dead trees). The box boundaries indicate the 25th and 75th percentiles, the solid line within the box marks the median, error bars indicate the 90th and 10th percentiles. BF = balsam fir, BS = black spruce.

Table 4
Fixed parameters, estimates, associated standard errors and p-values of the fixed effects estimates for the linear mixed models describing the relationship between moisture content (dry or wet basis) and tree species for different levels of wood decomposition.

	Estimates	Std. error	P-value
Dry			
Hunter 1 (Living)	102.42	7.81	<0.001
Species (BS)	−27.03	8.64	0.003
Hunter 2 (Living but declining)	−19.49	10.41	0.07
Hunter 3 (DSW)	−28.58	10.62	0.01
Hunter 4 (DSW)	−36.83	10.62	0.001
Wet			
Hunter 1 (Living)	50.6	2.56	<0.001
Species (BS)	−9.36	2.84	0.002
Hunter 2 (Living but declining)	−6.4	3.42	0.07
Hunter 3 (DSW)	−9.09	3.49	0.01
Hunter 4 (DSW)	−14.01	3.49	0.001

resented, while for black spruce the difference increased with tree size.

Among the scenarios presented in Fig. 7 (*i.e.*, Scenarios 3 and 4), wood chips for pulp (Scenario 3) appeared as the best economic option. The scenario in which tree stems were used to produce industrial wood pellets for the European market was the least advantageous. Again, the difference in profitability between each option varied significantly with stem size (Fig. 7). As DBH increased, it became increasingly advantageous to produce wood chips for pulp (Scenario 3).

Overall, dead trees ranging from 10 to 15 cm in DBH offered about equivalent financial potential between all scenarios (*i.e.*, nearing the profitability threshold in all cases). Both tree species offered about the same potential profitability for the three different levels of wood degradation analyzed.

3.3. Simulations at the stand level

According to the different harvesting scenarios simulated at the stand level for different times since the last fire and times since the start of an insect outbreak, harvesting dead trees along with live trees can provide profitability (Figs. 8 and 9). In the former of these two chronosequences, the proportion of interspersed dead trees varies throughout the course of forest succession but the characteristics of live trees remain unchanged. In the latter, the proportion of dead trees in the stand increases and the overall health and productivity of other trees in the stand are affected. From a sawmill perspective, harvesting both live and dead trees for the production of conventional products provided the highest benefit (Scenario 1), while harvesting dead trees for the production of pellets only provided the lowest benefit (Scenario 4). Producing pellets from dead trees as a co-product of lumber (Scenario 2) provided the second most profitable processing option. Producing pellets from dead trees (Scenario 4) provided the least profits in all cases. However, the gap in profitability between the option of producing pellets for European market (Scenario 4) and wood chips for pulp (Scenario 3) was rather small (Figs. 8 and 9).

Meanwhile, post-insect outbreak simulations showed a decrease in stand profitability with time since disturbance (Fig. 9) because stand profitability decreases with increasing proportion of dead trees at the stand level (Table 6). Similar results were obtained with time since the last fire, although the proportion of interspersed dead trees follows a different pattern in this case. Stand profitability increased from year 87 to 111 post-disturbance, mainly because of an increase in stocking (Table 5). A decline was observed at year 196 after fire, but higher profits were generated in the oldest forests (>200 years after fire). When the proportion of dead trees was too high (Tables 5 and 6), it became obvious that it was impossible to achieve high profitability for the production of wood pellets (*e.g.*, Figs. 8a and 9). However, when the proportion of dead trees was smaller, differences between scenarios became less noticeable (*e.g.*, Fig. 8b).

3.4. Sensitivity analysis

The sensitivity analysis suggested that a 20% drop in pulp price would extend to 20 cm in DBH the range of tree sizes for which Scenarios 3 and 4 are almost equivalent (Fig. 10). However, a 40% drop in pulp price would be necessary for Scenarios 3 and 4 to

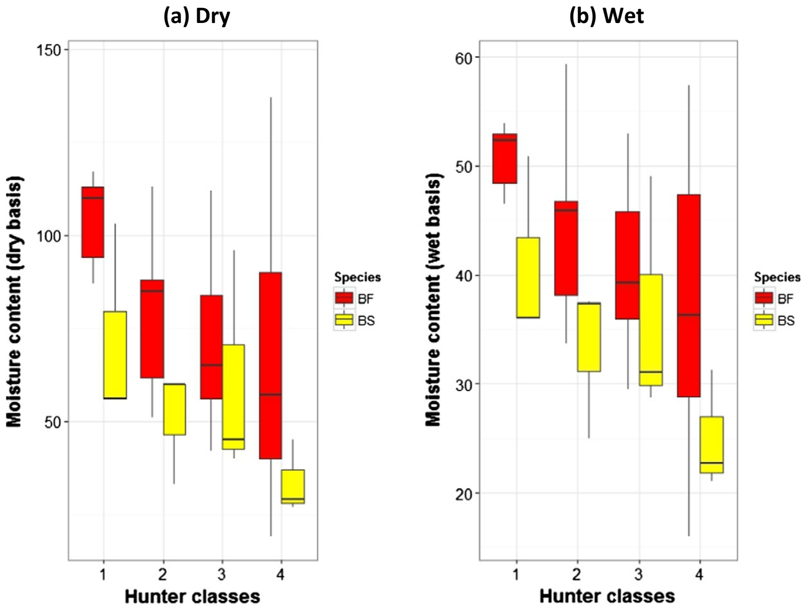

Fig. 4. Boxplots of moisture content (dry or wet basis) according to species and Hunter classes (Hunter 1 and 2 = live trees, Hunter 3 and 4 = dead trees). The box boundaries indicate the 25th and 75th percentiles, the solid line within the box marks the median, error bars indicate the 90th and 10th percentiles. BF = balsam fir, BS = black spruce.

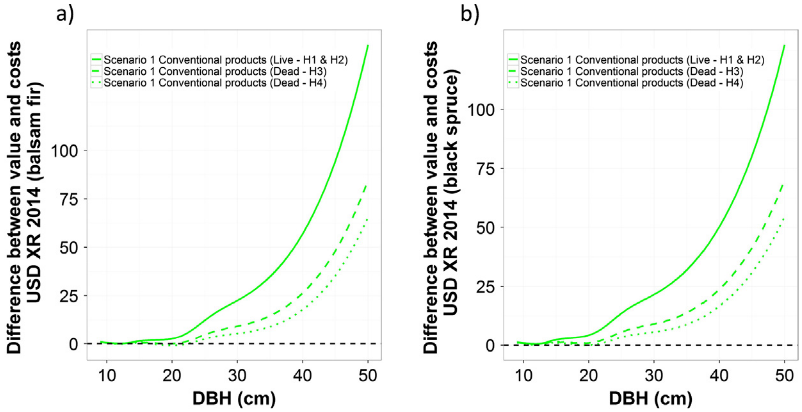

Fig. 5. Difference between value and costs for an eastern Canadian sawmill producing conventional forest products from balsam fir (a) and black spruce (b) trees of different sizes and degradation levels.

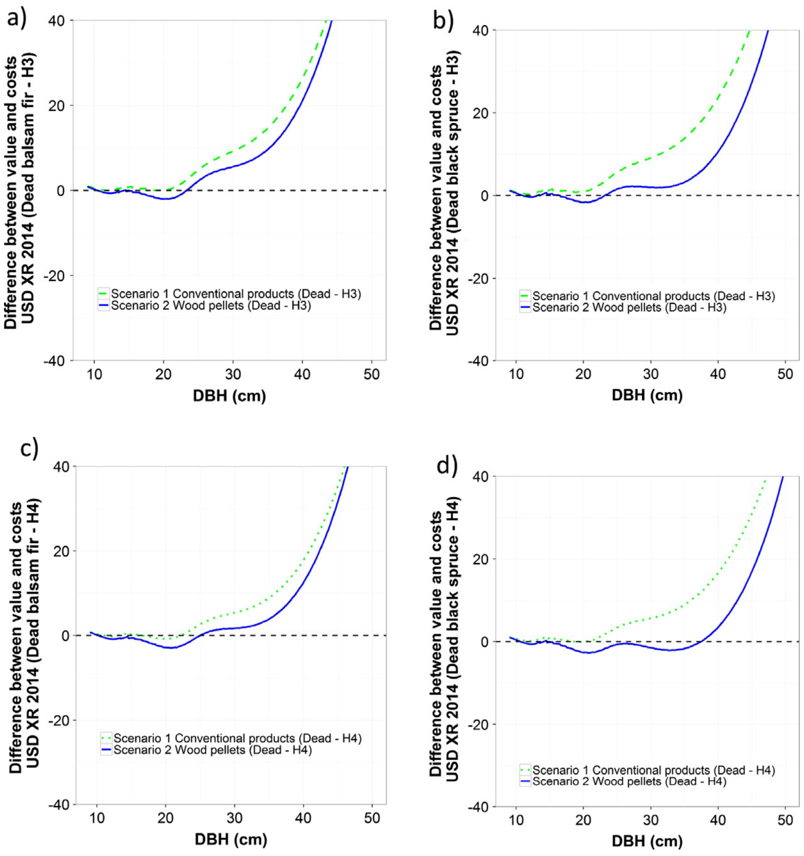

Fig. 6. Difference between value and costs for an eastern Canadian sawmill producing conventional products (Scenario 1) and conventional products with more pellets (Scenario 2) from balsam fir and black spruce of different sizes and degradation levels (Hunter 3 & 4).

become entirely equivalent for both tree species and wood degradation levels (Fig. 11).

4. Discussion

The scarcity of economic assessments of forest bioenergy production in the Canadian context can be explained by various factors, among which we can identify the commercial sensitivity of the financial information. In our analysis, we combined a wide range of information sources to estimate the cost and revenues associated with our scenarios. This, in itself, brings a fundamentally novel aspect to our study. One of our main findings is that in the current financial context, lumber production remains key in ensuring the profitability of dead tree harvesting for an eastern Canadian sawmill, and the most plausible source of feedstock for bioenergy should be the co-products of lumber sawing. For live trees, the preferred option was to produce lumber and sell co-products to a neighboring pulp plant. For dead trees, the preferred option might differ, despite higher profitability, due to sensitivity of pulp mills to feedstock quality. Moreover, the potential contri-

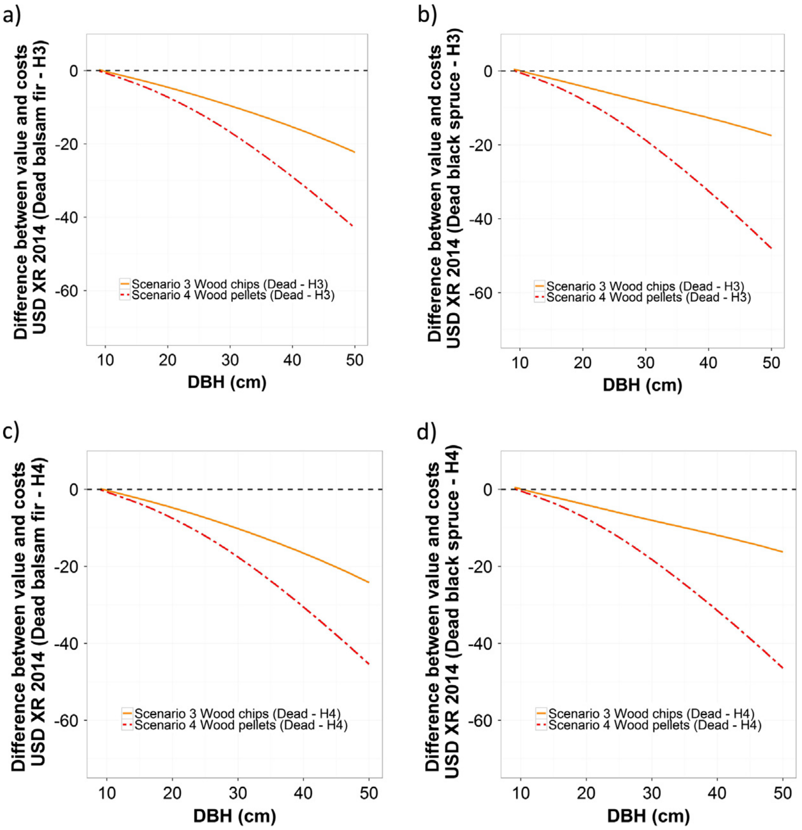

Fig. 7. Difference between value and costs for an eastern Canadian sawmill producing wood chips for a neighboring pulp plant (Scenario 3) or supplying whole trees for its own pellet mill (Scenario 4) using balsam fir and black spruce trees of different sizes and degradation levels (Hunter 3 & 4).

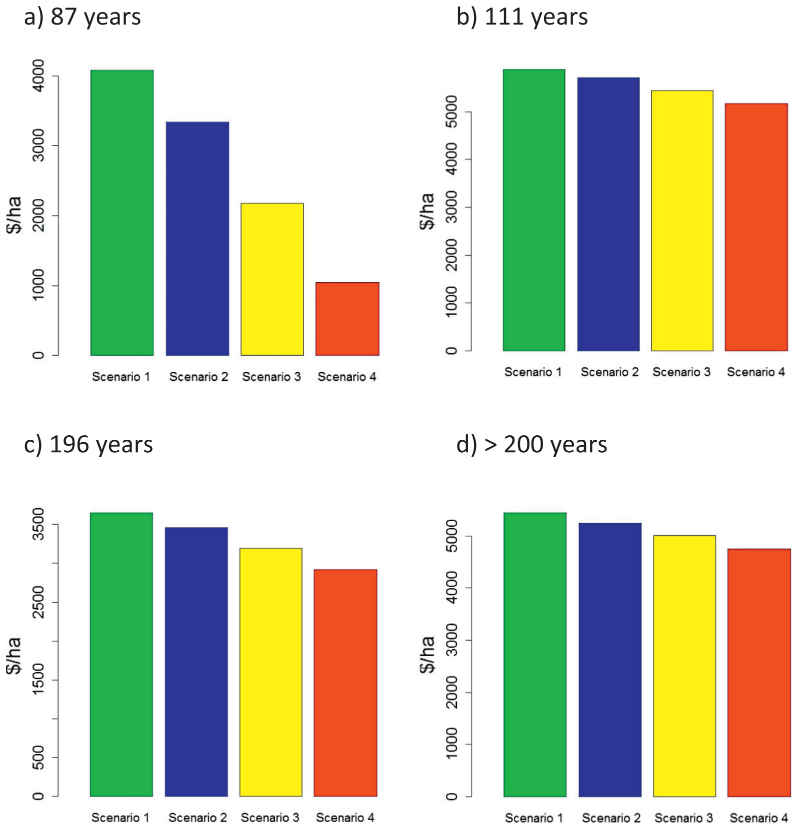

Fig. 8. Stand-level profits ($/ha) of the various dead tree scenarios at different times since fire (TSF). These time sequences are presented at (a) 87 years, (b) 111 years, (c) 196 years and (d) >200 years.

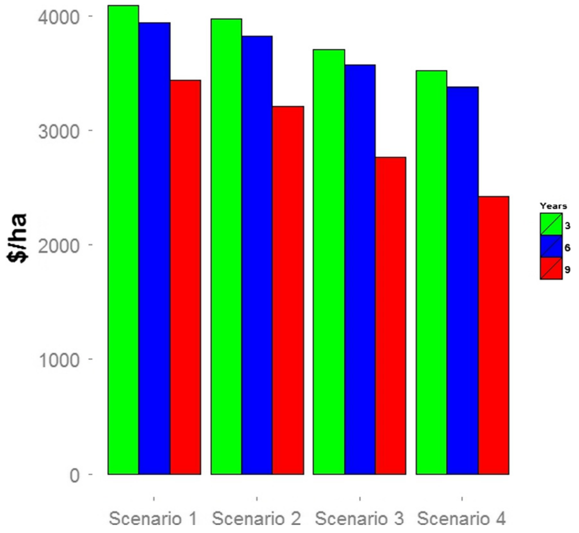

Fig. 9. Stand-level profits ($/ha) of the various dead tree scenarios, using data from the spruce budworm trial at different times since the start of epidemic (TSE) (3, 6 and 9 years).

bution of dead trees to respond to the increasing global demand for feedstock for bioenergy production in the context of climate change influence these processing decisions.

Usually, pulp mills seek wood chips from live trees since the uniformity of chip supply is an important criterion that affects the performance of a pulp and paper mill [65,66]. Dead trees generally contain a high proportion of wood rot [38] and low moisture content, both of which complicate the pulping process [67–69]. As observed in this study, the loss in moisture content varies between species and tree degradation levels. There was no loss in wood density with increasing tree degradation levels (Hunter 1–4). In contrast with pulp production, the moisture content and wood density was not found to be a deterrent for pellet production [44]: in fact, it could represent significant cost savings at the drying stage. Meanwhile, the degradation caused by brown-rot fungi increases the relative proportion of lignin, which acts as a natural binder and could save costs in pellet densification [70,71]. Therefore, there might be hidden cost savings associated with diverting lumber co-products to a pellet mill (Scenario 2) that were not taken into account in our study. Our study shows that for an eastern Canadian sawmill, the difference between Scenarios 1 and 2 remains small for any tree size (especially balsam fir). Pulp plants usually have a cost penalty system when the supply of chips from independent sawmills contains excessive amounts of rot. Due to the confidential nature of such contracts, this could not be taken into account in this study. However, it is reasonable to assume that even small penalties would therefore make Scenario 2 a desirable option in this case. Moreover, for a sawmill to have several alternative pathways for its co-products increases the resilience of its value chain, making it possible to adapt to temporary or permanent changes in markets.

An interesting point about budworm-killed trees is that balsam fir is more vulnerable to such attacks [72,73] and this species had closer values between Scenarios 1 and 2 than black spruce. However, the differences between species shown in this analysis must be interpreted with caution. A number of factors in our analysis explain the differences observed. First, in StatSAW, the production of lumber increased more abruptly in large balsam fir stems than in black spruce, (*i.e.*, in trees with DBH larger than approximately 27 cm - please refer to Fig. A3 in the appendix). Second, black spruce is much denser than balsam fir, which tends to increase weight-based transport costs calculated in this study. In reality, a full truck load of denser black spruce material might not exceed the weight limit for road transportation, possibly making the higher wood density financially advantageous. Third, our processing costs at the sawmill did not consider the higher drying cost associated with the higher MC of balsam fir.

Most scenarios provided about the same profitability for trees with DBH smaller than 15 cm. This suggests that the choice to process small trees for the production of lumber or not (*i.e.*, Scenarios 1 and 2 *vs.* 3 and 4) will have little impact on the profitability of the sawmill. In a situation where there is a shortage of feedstock for either wood pellet or pulp production, a sawmill could easily adjust by changing the diameter threshold over which logs are processed for lumber. Stem diameter is a known limiting factor for the lumber value recovery of small stems from the boreal forest of eastern Canada [74]. Using large dead trees for wood pellet production (Scenario 4) does not appear to represent a viable option under current market prices, unless suitable subsidies or other financial supports could be provided.

At the stand scale, using dead trees for bioenergy production was expected to help offset fixed costs for conventional products and hence be financially advantageous in stands where significant

Table 5
Number of stems per hectare, and mean, minimum and maximum diameter at breast height of live (Hunter 1 and 2) and dead (Hunter 3 and 4) trees in the interspersed trial.

Time since fire (years)	Stems/ha		Mean diameter (cm)		Min diameter (cm)		Max diameter (cm)	
	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)
87	825	525	17.3	15.8	10.0	10.9	28.0	22.6
111	1225	200	17.5	13.0	10.0	10.8	28.0	21.3
196	1275	75	15.2	18.7	10.0	13.3	34.0	24.0
>200	1400	175	15.8	14.6	10.0	11.1	32.0	18.0

Table 6
Number of stems per hectare, and mean, minimum and maximum diameter at breast height of live (Hunter 1 and 2) and dead (Hunter 3 and 4) trees in the spruce budworm trial.

Time since epidemic (years)	Stems/ha		Mean diameter (cm)		Min diameter (cm)		Max diameter (cm)	
	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)	Living trees (H1 and H2)	Dead trees (H3 and H4)
3	716	26	17.9	24.2	9.2	8.9	47.8	30.6
6	696	43	17.9	21.1	9.2	9.6	48.2	33.6
9	544	172	18.5	16.0	9.0	10.7	48.4	45.7

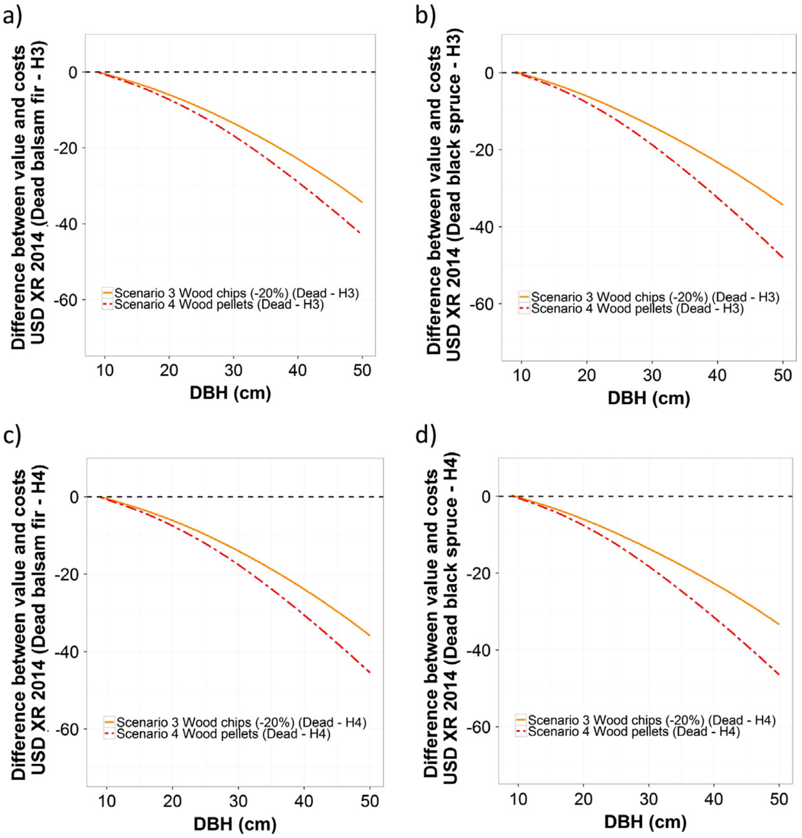

Fig. 10. Difference between value and costs for an eastern Canadian sawmill producing wood chips (Scenario 3) at a reduced pulp price (−20%) for a neighboring pulp plant or supplying dead trees for its own pellet mill (Scenario 4) using balsam fir and black spruce of different sizes and degradation levels.

mortality had occurred. However, this was not observed: our results suggested that stand-level profitability was mostly influenced by basic stand characteristics such as the number and size of stems per hectare (both of live and of dead trees) (see Tables 5 and 6).

Some uncertainties remain regarding the transport costs used in our simulations, which were based on roudwood from live trees, since there was no data available on transport costs for dead trees. However, savings might be made on the transport of dead trees since they are drier, which could contribute to increasing the profitability of processing dead trees [75].

Other factors outside of this analysis, such as the cost of site preparation and future forest health, could also influence the overall profitability of dead tree recovery. Recovery of forest biomass can be seen as an integral part of the silvicultural toolbox to manipulate microsite availability and quality for regeneration [76]. According to Puttock [77], the recovery of forest biomass through integrated harvesting operations in eastern Canada can lower the cost of site preparation by 25–50%.

Obviously, the financial analysis performed in this study depends greatly on the price list, exchange rates and cost estimations used at the time of the analysis. The sensitivity analysis revealed that the tipping point at which it becomes more profitable for a sawmill to use lumber co-products from dead trees for its own pellet mill than selling them to a nearby pulp plant is not too distant relative to current price conditions, especially if we consider that such feedstock is usually considered as undesirable by pulp producers. Indeed, the wood chip price used in our simulations can be assumed to represent the value of desirable feedstock (*i.e.*, no penalties for excessive rot). This price has fluctuated significantly over the past 10 years, with the average ranging from of 100 USD/ODT to 136 USD/ODT between 2005 and 2014 (Random Length's Yardstick 2005–2014). In the past 5 years, wood chips price have decreased by about 20%. An additional drop would certainly increase the financial relevance of the production of wood pellets, at least in the case of small dead stems, which can be abundant after insect outbreaks in pre-mature stands.

In the Southern US, it was determined that producing pellets for export to Europe (Rotterdam, the Netherlands) can be considered as a fairly attractive investment as long as the FOB price reaches 160 USD/t or more [78]. The cost of producing wood pellets was estimated to be around 50 USD/ODT in the US [78,79]. The feedstock supply cost from the forest to the pellet mill varies significantly with the distance involved, but Qian and McDow [78] reported numbers varying between 50 USD/ODT and 70 USD/ODT.

In our study, the cost of producing wood pellets compared favorably with that of the southern US (55 USD/ODT *vs* 50 USD/ODT). However, feedstock supply costs in eastern Canada are much higher. We estimated an average feedstock supply costs of about 124 USD/ODT, which includes stumpage (106 USD/ODT without stumpage), transport and felling costs (using an average tree DBH of 18 cm). This comparison suggests that the feedstock supply costs are probably the key factor to determine whether pellet production from salvaged dead trees in eastern Canada will have a significant impact on the international trade of bioenergy.

In this study, the feedstock supply costs for the production of wood pellets from dead trees were based on costs for conventional products [80]. However, feedstock used for the production of biomass is often chipped directly on-site, either at the roadside or inside the cutting block. To do this, the feedstock supply needs to be clean, as dirt and rocks affect chippers and decrease the desirability of the feedstock for wood pellet production [81]. In addition,

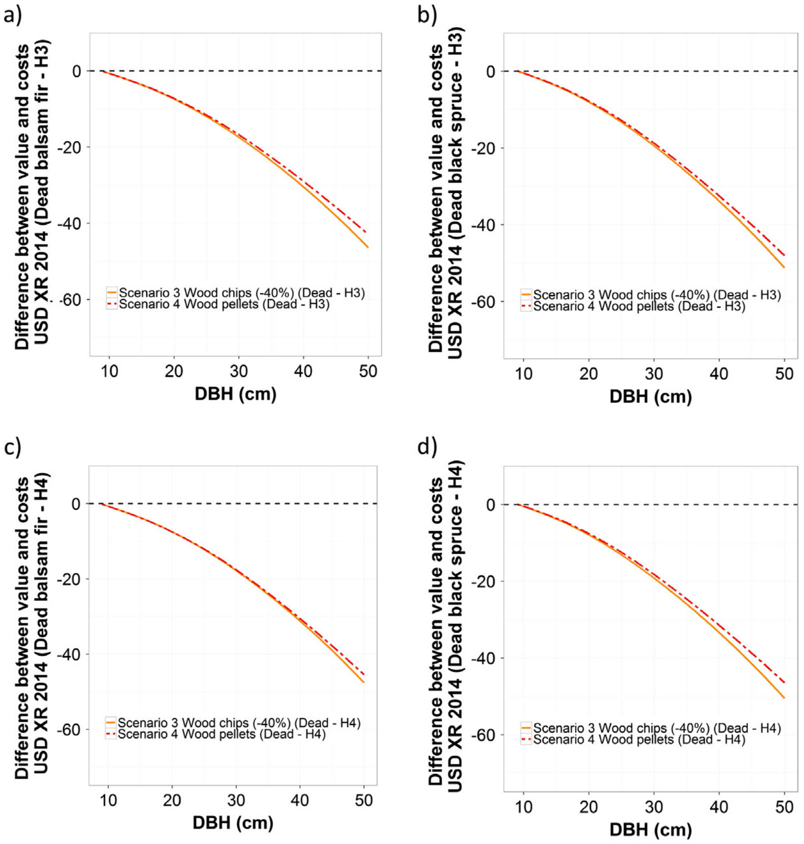

Fig. 11. Difference between value and costs for an eastern Canadian sawmill producing wood chips (Scenario 3) at a reduced pulp price (−40%) for a neighboring pulp plant or supplying dead trees for its own pellet mill (Scenario 4) using balsam fir and black spruce of different sizes and degradation levels.

processing dead trees with chippers or hoggers does not allow for debarking, thus reducing the chances of producing pellets that meet the best specifications of the ISO (ISO 17225-2 for industrial wood pellet) [82] standards provided by the EN ISO standards in Europe [83].

5. Conclusion

This financial analysis presents the potential profitability for different uses of dead trees from the boreal forest. The analysis was performed from the standpoint of an eastern Canadian, independent sawmill, the most prominent lumber processing facility in this region. Our analysis included the sawmill diverting dead trees to its own pellet mill and then selling the pellets overseas. The export of pellets from eastern Canada is a sector still in its infancy. Our results suggest that the presence of large trees that can generate value through lumber production remains key to ensuring their profitability. However, using dead trees for the production of lumber and industrial wood pellets for export to Europe is almost as profitable as using dead trees for the production of conventional products (lumber and wood chips for pulp). Under current conditions, producing pellets from dead trees does not appear to represent a financially viable option. Subsidies or other sources of financial support from the governments may thus be required. The sustainability criteria that are increasingly being applied to bioenergy production in Europe could stimulate such support, notably because of the international recognition of dead trees as an ecologically viable source of feedstock.

From the perspective of the sawmill, to have several alternative pathways for its co-products increases the resilience of the value chain, making it possible to adapt to temporary or permanent market changes and take full advantage on the emerging bioeconomy [43]. Dead trees generally contain a high proportion of wood rot and have lower moisture content, both of which affect paper quality and complicate the pulping process; they are hence often considered as a contaminant in the pulp industry. Considering the issue of chip quality for pulp mill, this result alone could bring significant changes in the structure of the Canadian forest value chain in future years. However, our results may also highlight the need to focus on higher added-value products: dead trees could be used as an interesting feedstock to make other type of products such as liquid biofuels [84]. Using our study as the baseline scenario, further research could therefore explore financial scenarios of using dead trees as feedstock for the production of a full suite of fuels and bioproducts.

With renewable energy and global climate targets, the demand for forest biomass in the longer term is unlikely to decline and feedstocks to fulfill this demand will constantly be sought. An increasing demand could drive up prices for pellets, which would change the economic profitability of this conversion pathway relative to pulp production, for example. With the opportunity of adding value to under-utilized or non-desirable feedstocks such as dead trees, bioenergy/biofuel producers might enhance the resilience of the forest sector while avoiding competition for fiber.

Acknowledgments

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Appendix A

See Figs. A1–A3 and Tables A1 and A2.

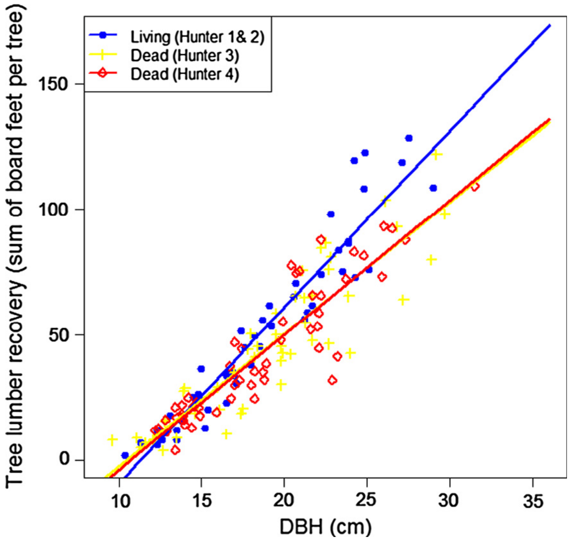

Fig. A1. Tree lumber recovery expressed as the sum of board feet per tree in relation to tree DBH and tree degradation level for black spruce. 1000 board feet = 2.36 m^3.

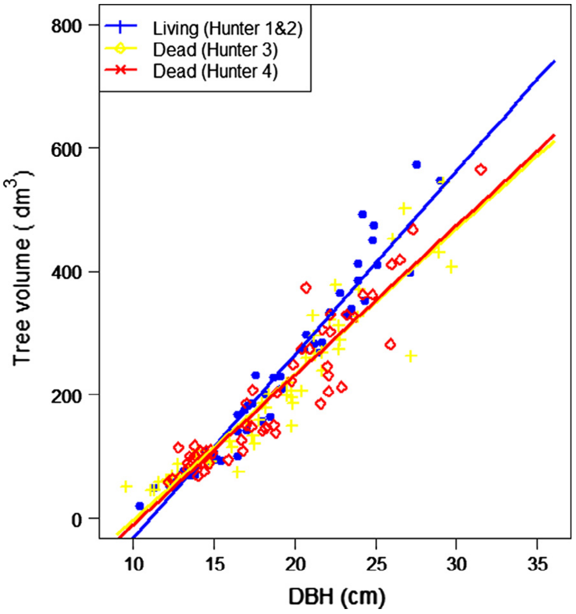

Fig. A2. Tree volume in relation to tree DBH and tree degradation level for black spruce.

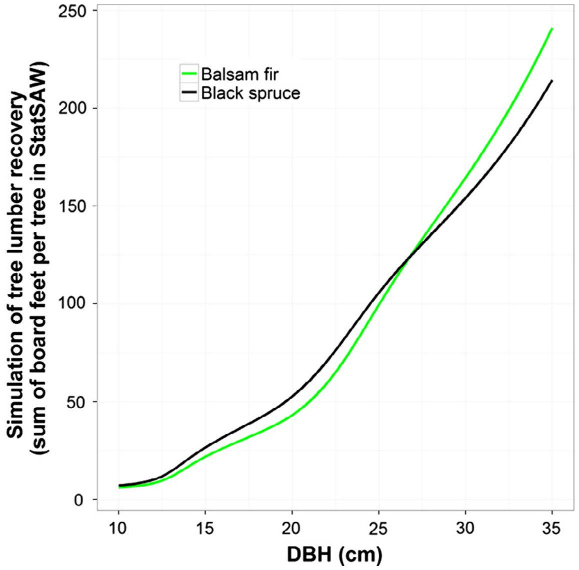

Fig. A3. Simulation of tree lumber recovery expressed as the sum of board feet per tree in StatSAW in relation to tree DBH and tree species.

Table A1
Fixed parameters, estimates, associated standard errors, p-values and standard deviation of the random effect estimates for the linear model describing the relationship between tree lumber recovery (expressed as the sum of pmp per tree) and tree DBH for different levels of wood degradation.

	Estimates	Std. error	p-value
Hunter 1& 2 (Living)	−79.89	6.41	<0.001
DBH	7.03	0.34	<0.001
Hunter 3 (DSW)	24.88	8.87	0.005
Hunter 4 (DSW)	22.35	9.2	0.016
DBH: Hunter 3	−1.77	0.46	<0.001
DBH: Hunter 4	−1.66	0.48	<0.001

Table A2
Fixed parameters, estimates, associated standard errors, p-values and standard deviation of the random effects estimates for the linear model describing the relationship between tree volume and tree DBH for different levels of wood degradation.

	Estimates	Std. error	p-value
Hunter 1& 2 (Living)	−331.07	23.08	<0.001
DBH	29.8	1.21	<0.001
Hunter 3 (DSW)	92.46	31.9	0.004
Hunter 4 (DSW)	77.09	33.11	0.021
DBH: Hunter 3	−6.22	1.66	<0.001
DBH: Hunter 4	−5.52	1.73	0.002

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