

# Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests

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## Abstract

Accurately assessing the delay before the substitution of fossil fuel by forest bioenergy starts having a net beneficial impact on atmospheric CO<sub>2</sub> is becoming important as the cost of delaying GHG emission reductions is increasingly being recognized. We documented the time to carbon (C) parity of forest bioenergy sourced from different feedstocks (harvest residues, salvaged trees, and green trees), typical of forest biomass production in Canada, used to replace three fossil fuel types (coal, oil, and natural gas) in heating or power generation. The time to C parity is defined as the time needed for the newly established bioenergy system to reach the cumulative C emissions of a fossil fuel, counterfactual system. Furthermore, we estimated an uncertainty period derived from the difference in C parity time between predefined best- and worst-case scenarios, in which parameter values related to the supply chain and forest dynamics varied. The results indicate short-to-long ranking of C parity times for residues < salvaged trees < green trees and for substituting the less energy-dense fossil fuels (coal < oil < natural gas). A sensitivity analysis indicated that silviculture and enhanced conversion efficiency, when occurring only in the bioenergy system, help reduce time to C parity. The uncertainty around the estimate of C parity time is generally small and inconsequential in the case of harvest residues but is generally large for the other feedstocks, indicating that meeting specific C parity time using feedstock other than residues is possible, but would require very specific conditions. Overall, the use of single parity time values to evaluate the performance of a particular feedstock in mitigating GHG emissions should be questioned given the importance of uncertainty as an inherent component of any bioenergy project.

**Keywords:** carbon debt, carbon dioxide emissions, carbon parity time, climate change, forest ecosystems, life cycle assessment, logging residues, renewable energy, salvage logging, wood pellets

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## Introduction

The use of forest-based bioenergy to replace fossil fuels in heat and electricity generation has the potential to reduce greenhouse gas (GHG) emissions. Under sustainable forest management practices, forests can provide renewable feedstock for bioenergy as the CO<sub>2</sub> released during wood combustion is later recaptured by photosynthesis as the forest regrows. However, the presumed 'C neutrality' of forest bioenergy has been the subject of much debate recently (Searchinger *et al.*, 2009; Manomet, 2010) because of the three following points: (i) Wood emits more CO<sub>2</sub> than fossil fuel per unit of energy released (Gómez *et al.*, 2006); (ii) the release of CO<sub>2</sub> is much faster when wood is combusted than when wood undergoes natural decomposition; and (iii) CO<sub>2</sub>

recapture by vegetation is not immediate and is usually achieved on decade- to century-long timescales. Therefore, there is a period of variable length during which cumulative CO<sub>2</sub> emissions to the atmosphere from an energy plant are greater for bioenergy than for fossil fuel. The delay before atmospheric GHG benefits are achieved has been referred to as C payback time (or C debt repayment time) when preharvest C levels are reached (absolute C balance), or as time to C parity when C levels of a reference case are reached (relative C balance) (see Lamers & Junginger, 2013, for a thorough discussion on terminology).

Canada is among the largest producers and exporters of solid bioenergy (Lamers *et al.*, 2012; Goh *et al.*, 2013). To date, case studies assessing the C debt and potential CO<sub>2</sub> emission savings of different forest bioenergy projects in Canada have yielded varying results, from instant atmospheric benefits to C payback/parity times of over 100 years. For example, cofiring pellets with coal

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in Ontario for electricity generation resulted in C debt repayment times of 16 and 38 years when pellets were made from harvest residues and green trees, respectively (McKechnie *et al.*, 2011). Using eddy covariance flux towers in Saskatchewan and Quebec to estimate net ecosystem exchanges, Bernier & Paré (2013) obtained a multidecadal time to C parity (>90 years) for a scenario that used wood chips from green trees to replace diesel oil in heat generation. A study in British Columbia forests impacted by the mountain pine beetle (MPB) (*Dendroctus ponderosae* Hopkins) showed that some scenarios had immediate atmospheric benefits (no C debt) and that using harvest residues and nonmerchantable trees for pellet production was more C beneficial than a stand protection alternative with no harvest (Lamers *et al.*, 2014).

Factors regulating the GHG mitigation potential of bioenergy projects and the underlying large variation in C parity times include biomass feedstock source and processing, the type of fossil fuel replaced, energy conversion efficiency, tree growth rate, and the definition of the counterfactual 'reference' scenario, that is, what would have happened to the forest land if biomass had not been sourced and used for bioenergy? (Lamers *et al.*, 2013; Buchholz *et al.*, 2014, 2015). Because many of those factors usually differ among studies, it is often difficult to compare C parity times among a variety of forest bioenergy uses. This situation stresses the need for a common accounting system to support decision-making (Buchholz *et al.*, 2015).

Furthermore, Buchholz *et al.* (2015) recommend that future studies assessing the C balance of bioenergy pathways consider quantifying and reporting uncertainties, which have rarely been addressed in past life cycle assessment (LCA) studies (e.g., Johnson *et al.*, 2011; Caputo *et al.*, 2014; Cherubini *et al.*, 2014; Röder *et al.*, 2015). Indeed, sources of uncertainty are encountered all along the supply chain as well as within the forest ecosystem, where various ecological factors may impact tree regeneration and decay rates. Understanding how variability in key parameters affects the mitigation potential of a bioenergy system is necessary to appreciate the full range of possible outcomes and make informed decisions and establish the right policies.

The aim of this study was therefore to compare, using a common framework, the mitigation potential and timing of atmospheric benefits for different bioenergy deployment scenarios sourcing their biomass from Canadian forests. Specific objectives were to quantify the uncertainties associated with such scenarios and identify how such uncertainties could be reduced to increase confidence in the timing and scale of GHG benefits for major forest bioenergy pathways. To this end, we developed a landscape-scale GHG emission calcula-

tor based on a LCA approach in which sources of variation and uncertainty are explicitly identified. Carbon parity times and their associated uncertainty were calculated for scenarios sourcing biomass from different feedstock types (harvest residues, salvaged trees (i.e., trees killed by natural disturbances), or green trees) typical of biomass production in Canada used to replace three fossil fuel types (coal, oil or natural gas) in heating or power generation. Results from this study may provide guidance for defining policies aimed at promoting the best forest bioenergy pathways for GHG mitigation. A free Web-based version of the calculator will be made available at <https://apps-scf-cfs.rncan.gc.ca/calc/en> (section GHG Bioenergy).

## Materials and methods

### Study area description

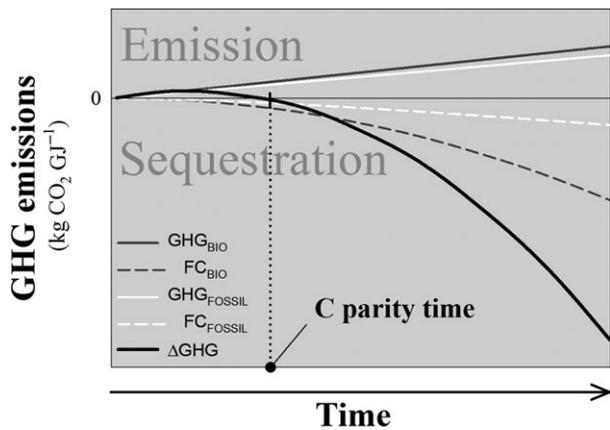
Our study focuses on the Canadian managed forest, which is estimated at 153 million ha (NRCan, 2014b). The area encompasses five terrestrial ecozones (i.e., Atlantic maritime, Boreal shield, Mixedwood plain, Montane cordillera, and Pacific maritime), where mean annual temperature (MAT) and mean annual precipitation range from  $-1$  to  $5$  °C and from 400 to 3000 mm, respectively (Environment Canada, 2015). On average (1990–2013), forest harvesting occurs on 1.0 million ha annually, whereas fire and insects disturb 3.1 and 19.1 million ha, respectively (NRCan, 2014a). Frequency and severity of natural disturbances are expected to increase in the future (Soja *et al.*, 2007; Boulanger *et al.*, 2014), potentially making salvage wood an increasing feedstock source for harvested wood products, which include bioenergy.

### Model framework for GHG accounting

The components of our LCA for GHG accounting include emissions from feedstock production and use, forest C dynamics, and energy conversion efficiency (Fig. S1). The GHG mitigation potential over time for a given bioenergy scenario needs to be assessed relative to a baseline, or counterfactual, scenario, which implies the use of fossil fuel. The GHG mitigation potential is calculated as follows:

$$\Delta\text{GHG}_t = \frac{\text{GHG}_{t\text{BIO}} + \text{FC}_{t\text{BIO}}}{\text{CE}_{\text{BIO}}} - \frac{\text{GHG}_{t\text{FOSSIL}} + \text{FC}_{t\text{FOSSIL}}}{\text{CE}_{\text{FOSSIL}}}, \quad (1)$$

where  $\Delta\text{GHG}_t$  is the cumulative difference in  $\text{CO}_2\text{eq}$  emissions between the bioenergy and fossil fuel scenarios at time  $t$  (in kg  $\text{CO}_2$  emitted per GJ of bioenergy produced),  $\text{GHG}_{t\text{BIO}}$  and  $\text{GHG}_{t\text{FOSSIL}}$  are cumulative emissions from the bioenergy and fossil fuel systems (production and use) at time  $t$ , respectively,  $\text{FC}_{t\text{BIO}}$  and  $\text{FC}_{t\text{FOSSIL}}$  are the forest C status (reported in  $\text{CO}_2$ ) of the bioenergy and fossil fuel systems at time  $t$ , respectively, and  $\text{CE}_{\text{BIO}}$  and  $\text{CE}_{\text{FOSSIL}}$  are the energy conversion efficiency of bioenergy and fossil fuel, respectively. When  $\Delta\text{GHG}_t$  reaches zero, the C parity time has been reached and GHG mitigation benefits begin to occur (Fig. 1). All emissions were derived



**Fig. 1** The C parity time concept illustrated using the current model framework for C accounting.  $GHG_{BIO}$  and  $GHG_{FOSSIL}$  are emissions from the bioenergy and fossil fuel systems (production and use), respectively;  $FC_{BIO}$  and  $FC_{FOSSIL}$  are the forest C status of the bioenergy and fossil fuel systems, respectively;  $\Delta GHG$  is the difference in  $CO_2$  emissions between the bioenergy and fossil fuel scenarios. When  $\Delta GHG$  reaches zero, C parity time has been reached and GHG mitigation benefits begin to occur.

from the production of 1 GJ of energy per year for a 100-year period (landscape-scale analysis). All modeling was performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

Our forest C analysis assumes constant soil C stocks although in theory a certain fraction of the deadwood decaying on the ground should eventually contribute to the soil C stock. Hence, some modeling results suggest that continual residue removal may permanently reduce forest floor C storage and delay time to C parity (Repo *et al.*, 2011, 2012). However, there is little empirical support for systematic and significant long-term mineral soil C changes following harvesting across the boreal and temperate forest biomes (Johnson & Curtis, 2001; Nave *et al.*, 2010; Thiffault *et al.*, 2011). In addition, forest floor C is usually quickly replenished as the forest regenerates (Nave *et al.*, 2010). In our opinion, additional research assessing long-term impact of residue removal on soil C is still warranted to consider with confidence soil C dynamics in forest bioenergy C accounting studies.

### Forest carbon dynamics in bioenergy and counterfactual scenarios

**Harvest residues.** Harvest residues are defined as all woody debris generated in harvest operations for traditional wood products (e.g., branches, tree tops, bark), excluding stumps and downed nonmerchantable trees. Harvest residues can be left on site to decompose or, as it is still the practice in parts of Canada, they can be piled by the roadside and burned under controlled conditions to reduce the fire hazard. In the case in which unused residues are burned by the roadside, the  $CO_2$  release from these residues happens nearly at the same time whether the energy is generated from biomass or from fossil

fuel, with no consequences for time to C parity. Combustion of the residues burned by the roadside is assumed to be complete although some fraction may contribute to the soil C pool in the form of charcoal. In the case in which harvest residues are not harvested for bioenergy and left on site to decompose, the multiyear delay in the release of  $CO_2$  must be accounted for in the GHG comparison between bioenergy and fossil fuel scenarios. In our calculator, we used the following exponential decay function to express  $CO_2$  release over time:

$$C_{tWD} = C_{0WD} \times e^{-k \times t}, \quad (2)$$

where  $C_{tWD}$  is the quantity of C (kg  $CO_2$ ) stored in woody debris at time  $t$  (years),  $C_{0WD}$  is the initial quantity of C stored in woody debris (kg  $CO_2$ ), and  $k$  is the decomposition rate of woody debris ( $year^{-1}$ ). Because temperature is the main driver of decomposition rates in these forests (Litton & Giardina, 2008; Laganière *et al.*, 2012), we used the temperature-dependent decay function of the Canadian forest C budget model CBM-CFS3 (Kurz *et al.*, 2009) to compute the decay rate ( $year^{-1}$ ) across the range of temperatures found in the Canadian managed forest:

$$k = BDR_k \times TempMod, \quad (3)$$

where  $BDR_k$  is the base decomposition rate of woody debris (aboveground fast pool =  $0.1435 \text{ year}^{-1}$ ) at a reference MAT of  $10 \text{ }^\circ\text{C}$ , and TempMod is the temperature modifier that reduces the decay rate for MAT below the reference MAT and is calculated as:

$$TempMod = e^{((MAT_f - RefMAT) \times \ln(Q_{10}) \times 0.1)}, \quad (4)$$

where  $MAT_f$  is the MAT of the forest area ( $-1$  to  $5 \text{ }^\circ\text{C}$  in Canada's managed forest), RefMAT is the reference MAT of  $10 \text{ }^\circ\text{C}$ , and  $Q_{10}$  is the temperature sensitivity of decomposition set at 2. Because  $BDR_k$  varies markedly among tree species (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014), we performed a sensitivity analysis on this parameter.

**Salvaged trees.** In scenarios sourcing their biomass from salvaged trees (i.e., standing trees killed by natural disturbances), the stemwood is harvested for bioenergy while the residues are left on site (i.e., the fate of the residues is not considered in the accounting). In the counterfactual scenario, the standing dead trees (i.e., snags) are assumed to start decaying immediately after tree death at a  $BDR_k$  of  $0.0187 \text{ year}^{-1}$  (Kurz *et al.*, 2009) following Eqn. 2, until they fall to the ground following Eqn 5, where they start to decay at a  $BDR_k$  of  $0.0374 \text{ year}^{-1}$  (Kurz *et al.*, 2009) following Eqn 2. The equation for snag C transfer to the ground is as follows:

$$C_{t\text{snag}} = C_{0\text{snag}} \times e^{-CTR \times t}, \quad (5)$$

where  $C_{t\text{snag}}$  is the quantity of C (kg  $CO_2$ ) stored in snags (standing woody debris) at time  $t$  (years),  $C_{0\text{snag}}$  is the initial quantity of C stored in snags (kg  $CO_2$ ), and CTR is the C transfer rate of snags ( $year^{-1}$ ) that varies between 0.04 and 0.10 (Hilger *et al.*, 2012).

**Green trees.** In scenarios sourcing their biomass from green trees (living biomass), we assume that only the stemwood is

harvested for bioenergy (tree tops and branches are left on site) and that no harvesting is carried out and there is only a negligible risk of disturbance in the reference forest in the counterfactual scenario. Because we consider harvesting of green trees for bioenergy to complement, not to compete with, that for traditional forest products, harvesting of green trees for bioenergy is viewed as 'additional harvesting' meaning that this feedstock would not be used in the counterfactual scenario due to various reasons (e.g., species unused by the traditional forest industry, fiber quality unsuitable for traditional products but suitable for bioenergy). Scenarios where the feedstock competes for its use (bioenergy vs. traditional products) were not explored in the current study.

The time required for the forest C of the bioenergy system to balance itself with that of the fossil fuel system depends on the regeneration rate of the harvested forest and also on the rate at which the forest continues to grow in the counterfactual scenario. We define three generic forest growth curves: fast, medium, and slow, reaching an age of maximum mean annual increment (MAI) at 45, 75, and 120 years, respectively (Fig. S2). We assume that a forest is harvested at age of maximum MAI. The time required to reach maximum MAI following harvesting is the time required for the harvested forest to recapture all of the biogenic CO<sub>2</sub> emitted in a year from the combustion of 1 GJ of biomass (112 kg CO<sub>2</sub>). Using this approach, we can convert absolute stand volume (m<sup>3</sup> ha<sup>-1</sup>) into relative measures of time required to reach the original stand volume in units of % of initial harvestable volume. To account for the growth of the reference forest that is not harvested and thus continues to sequester C, we use the portion of the curves that follows maximum MAI, that is, after reaching 100% harvested stand biomass regeneration (Fig. S2).

### Upstream emissions

**Biomass production in bioenergy scenarios.** The GHG emissions associated with biomass production include those related to biomass collection (harvesting, forest stand renewal, and road construction/maintenance), processing (chipping and pelletization), and transportation (transport to processing plant and to local or international market). We used an emission factor of 2.63 kg CO<sub>2</sub>eq GJ<sup>-1</sup> for roundwood collection (salvaged and green trees), averaged from values found in studies on Canadian forests (i.e., Magelli *et al.*, 2009; Meil *et al.*, 2009; McKechnie *et al.*, 2011; Pa *et al.*, 2012; Lamers *et al.*, 2014). For harvest residue collection, we used 0.84 kg CO<sub>2</sub>eq GJ<sup>-1</sup>, as in McKechnie *et al.* (2011). For roundwood and harvest residue chipping, we used 0.76 kg CO<sub>2</sub>eq GJ<sup>-1</sup> and 0.05 kg CO<sub>2</sub>eq GJ<sup>-1</sup>, respectively, as in Lamers *et al.* (2014). For the pelletization process, which includes drying, milling, and pelletizing, we used 2.14 kg CO<sub>2</sub>eq GJ<sup>-1</sup> for pellets made from harvest residues, and 10.45 kg CO<sub>2</sub>eq GJ<sup>-1</sup> for pellets made from roundwood (i.e., salvaged and green trees), as in Lamers *et al.* (2014).

**Fossil fuel production in counterfactual scenarios.** Upstream emissions for fossil fuels include extraction, distribution and storage, production, transmission, land-use changes, gas leaks, and flares. Emission factors used for coal, oil, and natural gas

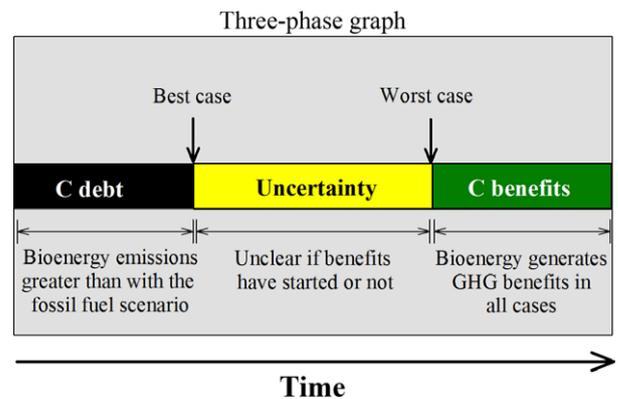
were 6.4, 14.9, and 9.0 kg CO<sub>2</sub>eq GJ<sup>-1</sup>, respectively ((S&T)<sup>2</sup>, 2015).

### Energy use

For coal, oil, and natural gas combustion, we used the following emission factors: 90.6, 71.1, and 50.3 kg CO<sub>2</sub>eq GJ<sup>-1</sup>, respectively ((S&T)<sup>2</sup>, 2015). For wood biomass, we used the default IPCC emission factor of 112.0 kg CO<sub>2</sub>eq GJ<sup>-1</sup> IPCC (2006). The conversion efficiency factors used for heat and electricity were 75% and 26% for biomass, 80% and 33% for coal, 82% and 35% for oil, and 85% and 45% for natural gas, respectively ((S&T)<sup>2</sup>, 2015).

### Scenario development (parameters and definition of uncertainty)

We calculated C parity time (in years) and potential emission reductions (in kg CO<sub>2</sub> GJ<sup>-1</sup>) of forest bioenergy sourced from different feedstocks (harvest residues, salvaged trees, or green trees) to replace three fossil fuel types (coal, oil, or natural gas) for two uses (heating or power generation). An uncertainty period was defined as the range in C parity times between predefined best-case (shortest C parity time) and worst-case (longest C parity time) scenarios for each scenario, with several potential cases lying in between (Fig. 2). To define the two end cases, we varied model parameters, including transportation distance to final users (local use or exportation), biomass processing (chips or pellets), and environmental characteristics (i.e., MAT, C transfer rate from snags to the ground). For example, for scenarios using harvest residues as feedstock, the best case implied: (i) collection of residues in the warmer part of our study area (MAT = 5 °C; the decomposition rate of residues left on site in the counterfactual scenario is high); (ii) processing into wood chips; and (iii) local use of wood chips (100 km of truck transport to final user). The worst case implied: (i) collection of residues in the colder part of the study area (MAT = -1 °C, which translates into a slow decomposition rate for biomass left on site in the counterfactual scenario); (ii) processing into pellets, which produces additional emissions



**Fig. 2** Three-phase graph used in the current study to represent estimates of C parity time and the associated uncertainty phase.

relative to wood chips; and (iii) transoceanic shipping from British Columbia to the United Kingdom (100 km by truck, 1000 km by train, and 16 000 km by vessel). Therefore, there are two types of parameters contributing to uncertainty: those based on choices related to the supply chain (i.e., transportation distance and biomass processing), and those based on variable ecological processes or environmental characteristics. Feedstock-specific details on the parameters defining the different cases are found above.

### Sensitivity analysis

A sensitivity analysis was performed on a set of bioenergy scenarios substituting coal in power production. We investigated how silviculture, energy conversion efficiency, and deadwood decay rate affected the performance of these scenarios (timing and uncertainty).

**Silviculture.** Because silvicultural operations (e.g., site preparation, tree planting, weed control) that increase tree growth following harvesting are widespread in Canada, we added scenarios where tree growth rate in the bioenergy system was 1.5 (Growth  $\times 1.5$ ), 2 (Growth  $\times 2$ ), and 2.5 (Growth  $\times 2.5$ ) times higher than that in the counterfactual fossil fuel system. In other words, age of maximum MAI of the forest is reduced by 1.5, 2, or 2.5 times in the bioenergy system relative to that in the counterfactual one. These estimates of potential growth increases via silviculture are conservative considering that the average timber yield in Canada forest is around  $1 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  while that of extensive plantations in Canada usually reaches  $2\text{--}6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Messier *et al.*, 2003; Paquette & Messier, 2010). Although regeneration failure (i.e., when predisturbance biomass levels are never recovered without proper forest management) may happen following clear-cut or natural disturbance (Lecomte *et al.*, 2006; Thiffault *et al.*, 2013), this possibility was not explored in the present study.

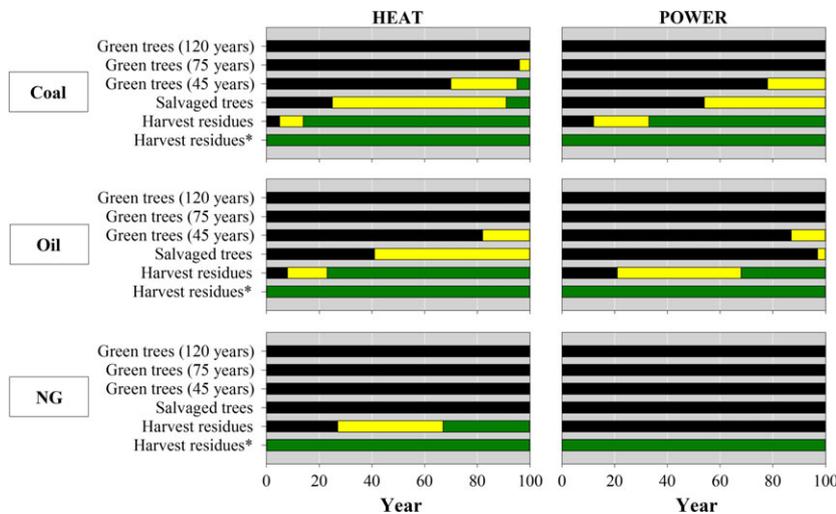
**Conversion efficiency.** We investigated how electricity conversion efficiency may affect timing and the uncertainty period by increasing the parameter from 26% to 35%, by 3% increments.

**Decay rate of woody debris.** Because the default base decomposition rate of CBM-CFS3 represents an average value that does not necessarily capture all the variability in decay rates among tree species across Canada, we performed a sensitivity analysis on selected scenarios (i.e., harvest residues and salvaged trees replacing coal in electricity generation) with elevated  $\text{BDR}_k$  (i.e., decomposition rate doubled or tripled) to reflect the faster decay rates of intolerant hardwood species such as aspen and birch (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014). These tree species usually have a low economic value and are often viewed as nonmerchutable by the industrial forest sector of timber and pulp.

## Results

### The uncertainty phase

The estimate of C parity time follows three temporal phases (Fig. 2): (i) a phase of C debt representing the period of time during which all cases for a given scenario, even the best case, do not provide any C benefits; (ii) a phase of C parity uncertainty, representing the range of C parity values between the best and the worst cases; and (iii) a phase of C benefits for all cases, during which even the worst cases provide C benefits. The length of the second phase, C parity uncertainty, during which it is unclear whether the benefits have started or not, varies from a few years to several decades and depends on the bioenergy feedstock, the type of fossil fuel replaced, silvicultural practices, energy conversion efficiency, and environmental characteristics. As shown in Fig. 3, the



**Fig. 3** Length of the C debt (black), uncertainty (yellow), and C benefit (green) phases for scenarios using different bioenergy feedstock to replace different fossil fuels for heat and power production. The asterisk indicates that harvest residues are burned by the roadside instead of left to decompose on the harvest site in the counterfactual scenario. NG: natural gas.

uncertainty is usually small for harvest residues, intermediate for green trees, and large for salvaged trees, and it increases with the efficiency of the fossil fuel in the following order: coal < oil < natural gas.

*The effect of biomass feedstock, type of fossil fuel replaced, and energy use*

Substitution of coal by forest bioenergy generates GHG emission savings over the shortest time frame, followed

by oil and natural gas (Table 1; Fig. 3). Except for some residue-based cases (i.e., heat generation), substitution of natural gas by forest bioenergy does not provide any atmospheric benefits within a 100-year period.

Immediate C benefits occur when bioenergy is sourced from residues normally burned by the roadside, irrespective of the choices in model parameters (Table 1; Fig. 3). Cumulative CO<sub>2</sub> emissions saved after 100 years vary from 4.6 to 11.8 Mg GJ<sup>-1</sup> for heat generation and from 6.5 to 28.6 Mg GJ<sup>-1</sup> for power production, depending on

**Table 1** Range of C parity time, uncertainty phase, and C balance for each best- and worst-case bioenergy scenario

Scenario	Carbon parity time		Carbon balance (Kg GJ <sup>-1</sup> )				
			25 years	50 years	100 years		
Feedstock	Fossil fuel	Use	(year)	Uncertainty phase (year)			
Harvest residues*	Coal	Heat	0	0	<b>-2449 to -2 962</b>	<b>-4897 to -5 923</b>	<b>-9795 to -11 846</b>
Harvest residues	Coal	Heat	5–14	9	<b>-571 to -1520</b>	<b>-2478 to -4 152</b>	<b>-6839 to -9 600</b>
Salvaged trees	Coal	Heat	25–91	66	1130 to <b>-11</b>	1249 to <b>-1327</b>	<b>-426 to -5592</b>
Green trees (45 years)	Coal	Heat	70–95	25	1914–1124	2487–907	<b>-778 to -3938</b>
Green trees (75 years)	Coal	Heat	96–>100	>4	1980–1190	3379–1799	2894 to <b>-265</b>
Green trees (120 years)	Coal	Heat	>100	>0	1886–1096	3768–2189	4917–1757
Harvest residues*	Coal	Power	0–0	0	<b>-5668 to -7148</b>	<b>-11 336 to -14 295</b>	<b>-22 672 to -28 590</b>
Harvest residues	Coal	Power	12–33	21	604 to <b>-1932</b>	<b>-2030 to -6561</b>	<b>-8626 to -16 264</b>
Salvaged trees	Coal	Power	54–>100	>46	4893–1764	7337–364	7585 to <b>-6394</b>
Green trees (45 years)	Coal	Power	78–>100	>22	6540–4261	8764–4207	<b>-67 to -9181</b>
Green trees (75 years)	Coal	Power	>100	>0	6871–4593	11 767–7209	11 651–2536
Green trees (120 years)	Coal	Power	>100	>0	6713–4434	13 243–8686	18 484–9370
Harvest residues*	Oil	Heat	0	0	<b>-2039 to -2552</b>	<b>-4078 to -5104</b>	<b>-8156 to -10 208</b>
Harvest residues	Oil	Heat	8–23	15	<b>-116 to -1054</b>	<b>-1535 to -3194</b>	<b>-4908 to -7652</b>
Salvaged trees	Oil	Heat	41–>100	>59	1552–420	2118 to <b>-434</b>	1384 to <b>-3734</b>
Green trees (45 years)	Oil	Heat	82–>100	>18	2304–1514	3243–1663	680 to <b>-2480</b>
Green trees (75 years)	Oil	Heat	>100	>0	2377–1587	4157–2578	4412–1252
Green trees (120 yrs)	Oil	Heat	>100	>0	2289–1499	4565–2986	6487–3328
Harvest residues*	Oil	Power	0	0	<b>-4462 to -5941</b>	<b>-8923 to -11 882</b>	<b>-17 847 to -23 765</b>
Harvest residues	Oil	Power	21–68	47	2068 to <b>-408</b>	1083 to <b>-3359</b>	<b>-2140 to -9679</b>
Salvaged trees	Oil	Power	97–>100	>3	6171–3091	10 034–3198	13 382 to <b>-318</b>
Green trees (45 years)	Oil	Power	87–>100	>13	7633–5354	10 815–6258	3734 to <b>-5380</b>
Green trees (75 years)	Oil	Power	>100	>0	8007–5728	13 947–9390	15 790–6676
Green trees (120 years)	Oil	Power	>100	>0	7882–5604	15 529–10 972	22 923–13 809
Harvest residues*	Gas	Heat	0	0	<b>-1162 to -1675</b>	<b>-2324 to -3350</b>	<b>-4649 to -6700</b>
Harvest residues	Gas	Heat	27–67	40	825 to <b>-98</b>	393 to <b>-1244</b>	<b>-988 to -3707</b>
Salvaged trees	Gas	Heat	>100	>0	2447–1327	3943–1425	5133–85
Green trees (45 years)	Gas	Heat	>100	>0	3152–2363	4907–3327	3933–773
Green trees (75 years)	Gas	Heat	>100	>0	3236–2446	5854–4274	7749–4589
Green trees (120 years)	Gas	Heat	>100	>0	3157–2367	6288–4708	9899–6740
Harvest residues*	Gas	Power	0	0	<b>-1615 to -3095</b>	<b>-3230 to -6189</b>	<b>-6460 to -12 378</b>
Harvest residues	Gas	Power	>100	>0	5859–3604	9343–5231	15 337–8158
Salvaged trees	Gas	Power	>100	>0	9281–6379	16 767–10 438	28 334–15 653
Green trees (45 years)	Gas	Power	>100	>0	10 063–7785	15 183–10 626	11 365–2 251
Green trees (75 years)	Gas	Power	>100	>0	10 594–8 315	18 788–14 231	24 661–15 547
Green trees (120 years)	Gas	Power	>100	>0	10 593–8315	20 760–16 203	32 896–23 782

The '>' sign is used when C parity time or uncertainty phase has reached the 100-year time boundary of this study and therefore cannot be estimated precisely. C balance with a negative sign (in bold) indicates that the bioenergy scenario generates net atmospheric benefit (sequestration) relative to the counterfactual scenario.

\*Harvest residues are normally burned by the roadside in the counterfactual scenario.

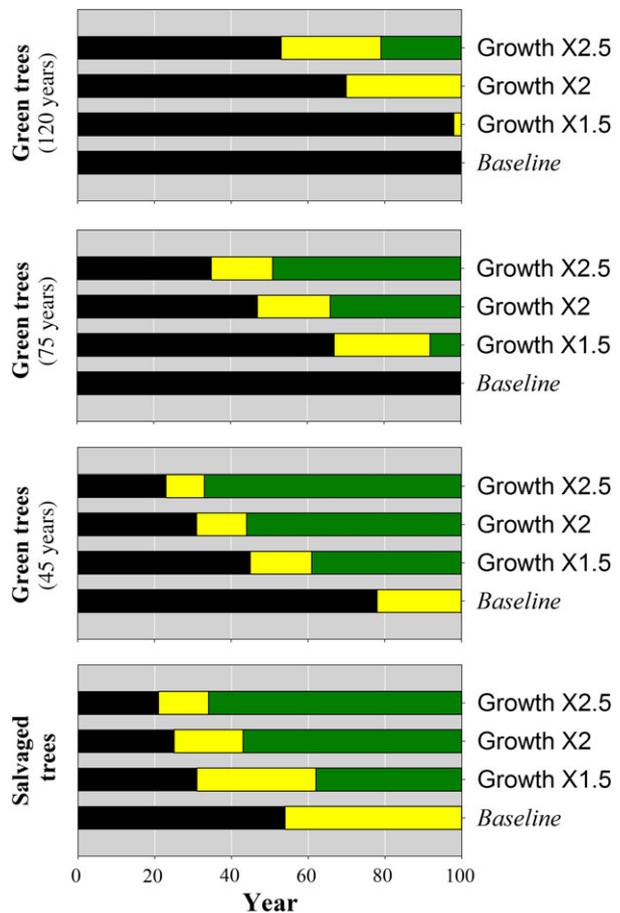
the type of fossil fuel replaced (Table 1). When bioenergy is sourced from harvest residues normally left to decompose *in situ*, C parity times range from 5 to 67 years for heat generation and from 12 to over 100 years for power production, depending on the type of fossil fuel replaced (Table 1; Fig. 3). Cumulative CO<sub>2</sub> emissions saved after 100 years are slightly lower than in the burned residues scenarios, that is, from 0.9 to 9.6 Mg GJ<sup>-1</sup> for heat generation and from no savings to 16.3 Mg GJ<sup>-1</sup> for power generation (Table 1).

When bioenergy is sourced from salvaged trees, C parity times range from 25 to over 100 years for heat production and from 54 to over 100 years for power production (Table 1; Fig. 3). Cumulative CO<sub>2</sub> emissions saved after 100 years for salvaged trees range from no savings to 5.6 Mg GJ<sup>-1</sup> for heat production and from no savings to 6.4 Mg GJ<sup>-1</sup> for power production (Table 1).

When bioenergy is sourced from fast-growing trees (age of maximum MAI = 45 years), C parity times range from 70 to 95 years for heat production and from 78 to 100 years for power production (Table 1; Fig. 3). Cumulative CO<sub>2</sub> emissions saved after 100 years vary from 0.8 to 3.9 Mg GJ<sup>-1</sup> for heat production and from 0.1 to 9.2 Mg GJ<sup>-1</sup> for power production (Table 1). When medium- or slow-growing trees are used (maximum MAI of 75 and 120 years, respectively), no emission savings generally occur on a 100-year time frame, except for medium-growing trees in the coal-heating scenario.

#### Sensitivity analysis

When silvicultural operations resulting in 1.5-, 2-, and 2.5-fold increases in tree growth rate are carried out, time to C parity and the length of the uncertainty phase are reduced (Fig. 4). Parity times of bioenergy sourced from salvaged trees to replace coal in power generation are under 62 years for 'Growth ×1.5', under 43 years for 'Growth ×2', and under 34 years for 'Growth ×2.5' (Fig. 4), with cumulative CO<sub>2</sub> emissions saved reaching 26.1, 40.2, and 54.6 Mg GJ<sup>-1</sup>, respectively (data not shown). When silvicultural operations are carried out, fast- and medium-growing trees may also become suitable feedstock options to achieve short- to medium-term mitigation benefits. Parity times for bioenergy sourced from fast-growing green trees are under 61 years for 'Growth ×1.5', under 44 years for 'Growth ×2', and under 33 years for 'Growth ×2.5', while parity times for bioenergy sourced from medium-growing green trees are under 92 years for 'Growth ×1.5', under 66 years for 'Growth ×2', and under 51 years for 'Growth ×2.5' (Fig. 4). Cumulative CO<sub>2</sub> emissions saved for 'Growth ×1.5', 'Growth ×2', and 'Growth ×2.5' reach 32.7, 54.0, and 77.6 Mg GJ<sup>-1</sup>, respectively, for fast-growing trees,

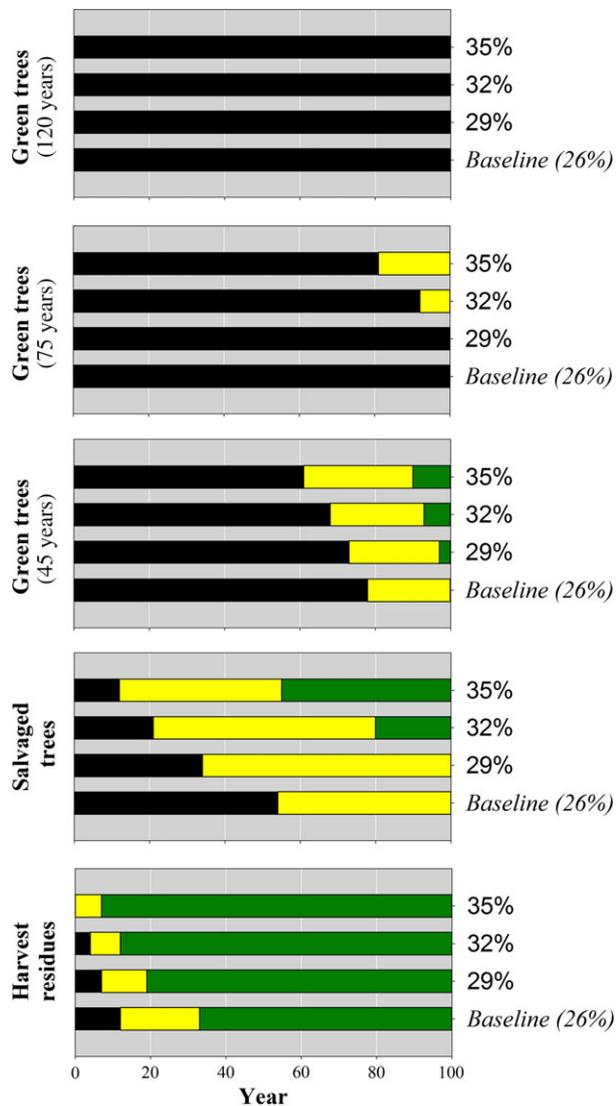


**Fig. 4** Timing of GHG benefits and length of the uncertainty phase of scenarios using different bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of silvicultural operations that increase the growth rate in regenerating forest stands by 1.5- (Growth ×1.5), 2- (Growth ×2), and 2.5-fold (Growth ×2.5) relative to the reference growth rate of forests in the counterfactual scenario. The 'no silviculture' scenario (baseline), in which growth rates are equal to the reference growth rate, is also shown.

while they reach 12.7, 26.9, and 41.2 Mg GJ<sup>-1</sup>, respectively, for medium-growing trees (data not shown).

Increasing energy conversion efficiency decreases time to parity of all bioenergy scenarios, but more so for salvaged trees (Fig. 5). Parity times of best-case scenarios using salvaged trees decrease from 54 years (without efficiency improvement) to 34 years with 3% improvement, to 21 years with 6% improvement, and to 12 years with 9% improvement. Moreover, improving efficiency by 9% allows the best case of the harvest residue scenario to achieve immediate benefits compared with 12 years without efficiency improvement (baseline scenario).

Increasing the basal decay rate (BDR) of the model by two and three times reduces parity time and the length

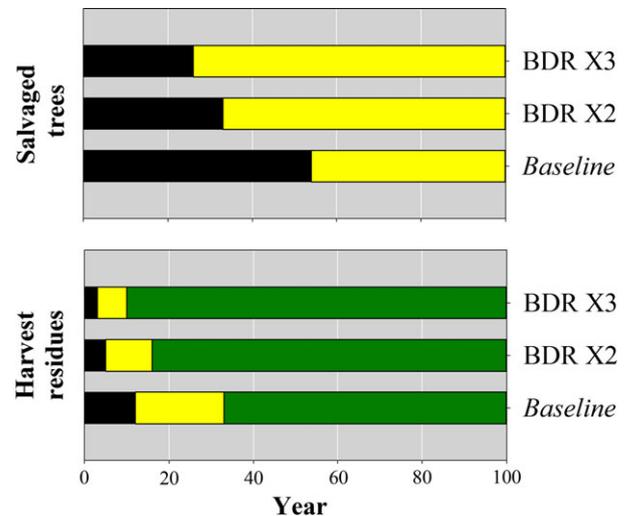


**Fig. 5** Timing of GHG benefits and length of the uncertainty phase of scenarios using different bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of enhanced energy conversion efficiency of biomass relative to a baseline value.

of the uncertainty phase (Fig. 6), but not as much as does the improvement of conversion efficiency (Fig. 5). Increasing conversion efficiency by 9% has a more beneficial effect on the reduction of C parity time of harvest residues than tripling the BDR.

#### *Decomposing the uncertainty*

In a scenario using salvaged trees to replace coal in power generation, the key parameters to reducing the length of the uncertainty phase and C parity time in the worst case are, in decreasing order of importance, transportation distance (local use vs. export), feedstock pro-



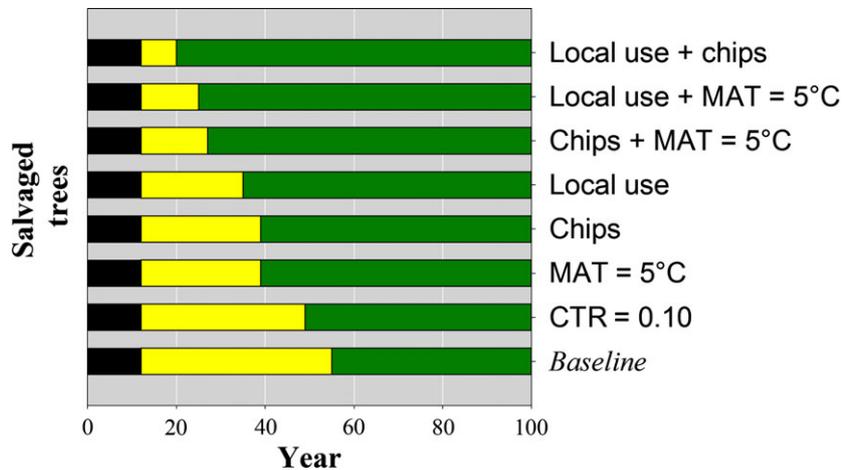
**Fig. 6** Timing of GHG benefits and length of the uncertainty phase of scenarios using salvaged trees and harvest residues as bioenergy feedstock to replace coal for power production. For each feedstock, scenarios show the effect of doubling and tripling the basal decay rate (BDR) of the model relative to the baseline rate to account for tree species decaying faster than average. BDR of the baseline scenario at a reference temperature of 10 °C is 0.144 and 0.037 year<sup>-1</sup> for residues and salvaged trees, respectively.

cessing (chips vs. pellets), and mean annual temperature (MAT = 5 vs. -1 °C), whereas the rate of C transfer from snag to the ground (CTR = 0.10 vs. 0.04 year<sup>-1</sup>) only has a minor effect (Fig. 7). This ranking is also true for scenarios involving different feedstock sources, fossil fuel types, and uses (results not shown).

## **Discussion**

### *Mitigation potential and timing of bioenergy sourced from Canadian forests*

Biomass feedstock and the type of fossil fuel replaced greatly affect the GHG mitigation potential and timing of forest bioenergy scenarios. The results indicate short-to-long ranking of parity times for residues < salvaged < green trees and for replacing the less efficient fossil fuels (coal < oil < natural gas). Not surprisingly, bioenergy sourced from harvest residues yielded the fastest atmospheric benefits. The uncertainty around the estimate of C parity time was also the smallest. Most studies documented parity times <20 years for bioenergy sourced from harvest residues excluding stumps (Repo *et al.*, 2011, 2012; Lamers & Junginger, 2013; Lamers *et al.*, 2014). Branches and tree tops are small woody debris that quickly decompose on the forest floor (Tarasov & Birdsey, 2001; Palviainen *et al.*, 2004; Preston *et al.*, 2012), and the parity time between the



**Fig. 7** Length of the uncertainty phase of scenarios using salvaged trees as bioenergy feedstock (with elevated conversion efficiency of 35%) to replace coal for power production. Uncertainty is generated through choices in parameter values for snag C transfer rates (CTR = 0.10 or 0.04 year<sup>-1</sup>), mean annual temperatures (MAT = 5 °C or -1 °C), biomass processing (chips or pellets), and transportation distances (local use or export). Scenarios are identified by which parameters are set as fixed while all others are varied to generate the uncertainty. For the baseline, all parameters are varied.

bioenergy system, in which biomass emits C to the atmosphere to produce energy, and the reference fossil fuel system, in which biomass is left to decompose in the forest, is therefore quickly reached. Furthermore, in the case of harvest residues that are normally burned by the roadside to reduce the fire hazard, the use of bioenergy to replace fossil fuel generates immediate atmospheric benefits (C parity time = 0 year). Likewise, increasing biomass conversion efficiency to 35% can generate immediate benefits in some cases of harvest residues normally left to decompose *in situ*. Given that the environmental cost of delaying GHG emission reductions is increasingly being recognized (IPCC, 2014), residue-based bioenergy therefore is a suitable feedstock for mitigating GHG emissions in a short time frame.

By contrast, using medium- and slow-growing green trees showed little to no atmospheric benefits over the 100-year period. In northern forests, trees grow slowly and harvested lands usually take many decades to regenerate and regain C levels that are similar to pre-harvest levels (Seely *et al.*, 2002; Kurz *et al.*, 2013). Furthermore, when the reference forest is assumed to be unharvested in the counterfactual scenario, CO<sub>2</sub> may still be taken up from the atmosphere while the land harvested for bioenergy slowly starts to regenerate. Accordingly, C parity time for procuring biomass from living trees takes many decades to be reached. Bernier & Paré (2013) obtained a time to C parity of over 90 years for a scenario that used wood chips from boreal tree species to replace oil in heat generation. Other studies also documented multidecadal parity times (or payback times) for bioenergy made from green trees in

northern forests (McKechnie *et al.*, 2011; Holtmark, 2012; Mitchell *et al.*, 2012; Ter-Mikaelian *et al.*, 2015). However, using silviculture to increase tree growth rate in the regenerating stand can improve the performance of this feedstock source and generate atmospheric benefits within a shorter time frame. Silvicultural practices as seen in Canada may increase timber yield from two to six times relative to natural forests (Paquette & Messier, 2010). Higher tree productivity and faster C capture through silviculture allow to reach parity time faster. Similar conclusions were obtained by the Ter-Mikaelian *et al.* (2015) study, in which coal was replaced by wood pellets sourced from Ontario forests. Moreover, Lamers *et al.* (2014) assumed faster tree growth (2×) for replanted sites relative to natural forests and obtained a parity time of 84 years for slow-growing spruce-fir stands, which falls well within our range of parity times for a comparable scenario (the one in which bioenergy is obtained from slow-growing green trees, i.e., 120 years). In summary, while using trees is most often associated with long-term parity time, some specific cases may show parity time <50 years. These cases would involve growth enhancement by silviculture, which would happen only with bioenergy scenarios and also good growing conditions (productive stand types with relatively short rotation periods).

Salvaged trees had intermediate parity times between that of harvest residues and that of green trees. This feedstock also had a very wide phase of uncertainty, indicating that some cases present reasonable parity times that meet short- and medium-term GHG emission reduction targets, while others do not. For example,

using bioenergy sourced entirely from slow-decomposing dead stemwood (e.g., pine species in cold regions) without regeneration improvement through silviculture is perhaps not an option to prioritize, given that the parity time would likely always be over 75 years. However, if silviculture is performed in the regenerating stand following harvesting and biomass procurement, this feedstock source may become more interesting in terms of C savings, with several cases falling below 40 years before achieving atmospheric benefits. Results from Lamers *et al.* (2014) also highlighted the potential of using salvage wood from MPB-impacted stands to mitigate GHG emissions. Relative to a reference 'no harvest' scenario, they obtained immediate benefits and a parity time of 22 years when pine-only (85% dead trees) and pine-dominated (62% dead trees) stands were first harvested for pellets, replanted (assuming a twofold growth yield in plantations relative to natural forest), and then harvested for sawlog timber with the residues used for pellets. Jonker *et al.* (2014) varied the forest management intensity levels and obtained >50% reduction in time to C parity in high-intensity management scenarios relative to low-intensity ones. In summary, as is the case for green trees, specific conditions need to be present to reduce the time to parity in salvaged wood scenarios. These conditions often involve silviculture. An interesting example is given in Barrette *et al.* (2013), where black spruce (*Picea mariana*) stands showed little regeneration 8 years after fire while jack pine (*Pinus banksiana*) stands showed a good regeneration. Harvesting biomass for bioenergy in the black spruce site would facilitate the silvicultural treatment carried out to restore forest productivity, while it would probably not enhance forest productivity in the jack pine site.

Increasing the base decomposition rate (BDR) of the model to account for tree species decaying faster than average indicates that sourcing bioenergy from fast-decomposing species such as intolerant hardwoods (e.g., aspen, birch) would be another potentially suitable GHG mitigation option, especially if the feedstock is collected in warmer regions. Although our knowledge of logs' decomposition rate is limited (Weedon *et al.*, 2009), empirical observations in northern forests showed that the logs of such species may achieve almost complete decomposition (85–95%) within 57 years, while pine and spruce species may take over 80 years (Tarasov & Birdsey, 2001; Brais *et al.*, 2006; Shorohova & Kapitsa, 2014).

Salvaged trees have the potential to generate relatively fast atmospheric benefits, but would require a good tracking system to reduce uncertainty and meet precise time frames. As shown in our analysis, favoring wood chips over pellets and local use over transoceanic export are good options to prioritize in order to reduce

the uncertainty period. Moreover, the speed at which parity time is reached is also impacted by the regional climate and tree species, which regulate the decomposition rate of deadwood (in the counterfactual scenario). Performing silviculture and improving energy conversion efficiency can also greatly reduce the time to GHG mitigation of bioenergy sourced from dead trees.

Overall, our results are coherent with the perspective of Haberl *et al.* (2012) on C emission reduction by bioenergy. Short- to medium-term atmospheric benefits (<50 years C parity time) must involve the use of 'additional biomass', defined as biomass from additional vegetation growth or biomass that would decay rapidly if not used for bioenergy. Such parity times are possible in some cases under salvaged tree scenarios, but more likely under specific conditions involving important gains in forest productivity (silviculture) under either green tree or salvage tree scenarios.

#### *Taking uncertainty into account*

To our knowledge, few studies have addressed the uncertainty around the estimation of C debt in a forest bioenergy context (Johnson *et al.*, 2011; Caputo *et al.*, 2014; Röder *et al.*, 2015). To date, studies have mostly focused on estimating a unique and precise C debt repayment time or C parity time for particular case studies without addressing any sources of variation. For correct accounting, however, estimates need to take uncertainty into account, from variations in the biomass supply chain to the realism of the counterfactual scenario (Johnson *et al.*, 2011; Bowyer *et al.*, 2012; Buchholz *et al.*, 2014, 2015). We found that the length of the uncertainty period can be short and inconsequential for some scenarios (e.g., harvest residues). However, for other scenarios, it can be large enough to cast doubts as to whether a particular feedstock should be considered in GHG mitigation efforts in the short term. In the current study, the length of the uncertainty phase depends on how we define the best and worst cases, that is, which parameters will vary and to what extent. In our scenarios involving green trees as feedstock, only upstream emissions (processing, transport) could affect uncertainty. By contrast, for salvaged trees, upstream emissions, MAT (which impacts the decomposition rate), and snag C transfer rate all are elements whose range of possible values contributed to uncertainty. These additional sources of variation explained the longer phase of C debt uncertainty in the salvaged tree scenarios relative to the green tree scenarios, while the slower decay rate of stemwood (salvaged trees) than of branches (residues) explained the longer uncertainty phase relative to harvest residues. Varying the tree growth rate in a scenario involving green trees (instead of making

separate scenarios) or adding natural disturbances (Buchholz *et al.*, 2015) would push the length of the uncertainty period for green tree-based scenarios beyond that of scenarios involving salvaged trees.

Not all sources of uncertainty were tested in our analysis. Some parameters including the emission factor for combustion of biomass and fossil fuel, fossil energy conversion efficiency, and temperature sensitivity of decomposition ( $Q_{10}$ ) were set as constants, based on averaged values found in the literature. The IPCC default emission factor for biomass combustion is  $112 \text{ kg CO}_2 \text{ GJ}^{-1}$ , but its 95% confidence limits range from 95 to  $132 \text{ kg CO}_2 \text{ GJ}^{-1}$  (IPCC, 2006). The heating value of wood also varies among tree species (Singh & Kostecy, 1986; Telmo & Lousada, 2011; Barrette *et al.*, 2013). Similarly, energy conversion efficiency for a given fossil fuel may vary substantially depending on factors such as generator capacity, age, and technology (Koop *et al.*, 2010). Jonker *et al.* (2014) varied the conversion efficiency of a coal power plant from 35% to 46% and observed decadal differences in payback and parity times of bioenergy under low- and high-efficiency scenarios. Röder *et al.* (2015) also pointed out the impact of wood chip storage duration on methane emissions, which greatly affect the C balance of forests and sawmill residues. As we gain confidence in understanding belowground processes and long-term impact of forest harvesting intensification, soil C (which was set as constant here) may become an important parameter to consider in the C balance of forest bioenergy, given the large share of ecosystem C that resides in soils (Laganière *et al.*, 2015). These additional sources of uncertainty could make the uncertainty phase even longer than what is presented here. Evidently, proper knowledge of both the bioenergy and the reference fossil fuel systems is required in order to accurately evaluate the potential of a bioenergy project to mitigate GHG emissions.

Key to reducing uncertainty around estimates of C parity time is a better assessment of ecological processes (e.g., forest regeneration and growth rate, decomposition dynamics), as also pointed out by Caputo *et al.* (2014). Favoring local use of wood chips over the export of wood pellets can also reduce the length of the uncertainty period. Potential economic feedback between biomass procurement practices and other forest management activities should also be considered: Adding bioenergy to the basket of products that can be sourced from a given stand or landscape may increase the profitability of overall forest operations and foresters' belief in future markets, creating new incentives for forest management (Bellassen & Luyssaert, 2014). Overall, the current study brings into question the use of single parity time values to evaluate the performance of a particular feedstock to mitigate GHG emissions

given the importance of uncertainty as an inherent component of every bioenergy project. More specifically, it suggests that some feedstock, such as green or salvaged trees that are usually associated with long and uncertain time to parity, can, under some very specific circumstances, show shorter and less uncertain parity times.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Simplified supply chain and system boundary of LCA when living biomass (i.e. green trees) and deadwood (i.e. harvest residues or salvaged trees) are used as a feedstock.

Figure S2. Stand regeneration curves used in scenarios sourcing biomass from green trees. Age of maximum mean annual increment (MAD) is reach at 100%.