GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2017) **9**, 1071–1084, doi: 10.1111/gcbb.12389

Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada

CAROLYN SMYTH[1], GREG RAMPLEY[2], TONY C. LEMPRIÈRE[2], OLAF SCHWAB[2] and WERNER A. KURZ[1]

[1]*Natural Resources Canada, Canadian Forest Service, 506 Burnside Road West, Victoria, BC V8Z 1M5, Canada,* [2]*Natural Resources Canada, Canadian Forest Service, 580 Booth Street, Ottawa, ON K1A 0E4, Canada*

Abstract

The potential of forests and the forest sector to mitigate greenhouse gas (GHG) emissions is widely recognized, but challenging to quantify at a national scale. Mitigation benefits through the use of forest products are affected by product life cycles, which determine the duration of carbon storage in wood products and substitution benefits where emissions are avoided using wood products instead of other emissions-intensive building products and energy fuels. Here we determined displacement factors for wood substitution in the built environment and bioenergy at the national level in Canada. For solid wood products, we compiled a basket of end-use products and determined the reduction in emissions for two functionally equivalent products: a more wood-intensive product vs. a less wood-intensive one. Avoided emissions for end-use products basket were weighted by Canadian consumption statistics to reflect national wood uses, and avoided emissions were further partitioned into displacement factors for sawnwood and panels. We also examined two bioenergy feedstock scenarios (*constant supply* and *constrained supply*) to estimate displacement factors for bioenergy using an optimized selection of bioenergy facilities which maximized avoided emissions from fossil fuels. Results demonstrated that the average displacement factors were found to be similar: product displacement factors were 0.54 tC displaced per tC of used for sawnwood and 0.45 tC tC^{-1} for panels; energy displacement factors for the two feedstock scenarios were 0.47 tC tC^{-1} for the *constant supply* and 0.89 tC tC^{-1} for the *constrained supply*. However, there was a wide range of substitution impacts. The greatest avoided emissions occurred when wood was substituted for steel and concrete in buildings, and when bioenergy from heat facilities and/or combined heat and power facilities was substituted for energy from high-emissions fossil fuels. We conclude that (1) national-level substitution benefits need to be considered within a systems perspective on climate change mitigation to avoid the development of policies that deliver no net benefits to the atmosphere, (2) the use of long-lived wood products in buildings to displace steel and concrete reduces GHG emissions, (3) the greatest bioenergy substitution benefits are achieved using a mix of facility types and capacities to displace emissions-intensive fossil fuels.

Keywords: Canada's managed forest, displacement factor, forest products, GHG emissions, local bioenergy, substitution impacts

Received 6 April 2016; accepted 13 July 2016

Introduction

Forest-related carbon (C) mitigation strategies offer important and viable pathways towards climate stabilization through increased use of harvested wood products (HWPs) that store C and avoid the consumption of emissions-intensive materials such as concrete and steel, and avoid emissions from burning fossil fuels for electricity or heat production (Pacala & Socolow, 2004; Böttcher *et al*., 2008; Sathre & O'Connor, 2010; Werner *et al*., 2010; Lundmark *et al*., 2014; Smyth *et al*., 2014). The potential greenhouse gas (GHG) emission reductions that can be achieved through substitution of wood products for other products and fossil fuels need to be quantified because substitution impacts are part of a larger systems approach which includes changes in forest C, HWPs tracking and substitution benefits (Smyth *et al*., 2014). Use of a systems perspective highlights trade-offs between activities aimed at increasing carbon storage in the ecosystem, increasing carbon storage in HWPs or increasing the substitution benefits of using wood in place of fossil fuels or more emissions-intensive products (Lemprière *et al*., 2013).

Displacement factors are used to describe the substitution benefit in mitigation strategies when wood is used instead of some other material (Schlamadinger & Marland, 1996). For wood products in the built

Correspondence: Carolyn Smyth, tel. +1 250 298 2313, fax +1 250 363 0775, e-mail: Carolyn.Smyth@canada.ca

environment, displacement factors are calculated from an end-use product, which typically includes building components or a complete building (e.g. Lippke *et al.*, 2004). However national-level mitigation strategies require a broader scope and need to derive a displacement factor for primary wood products (e.g. sawnwood and panels) based on a range of end-use products (e.g. homes, manufacturing, furniture), but displacement factors using this broader scope have not been estimated for Canada.

Our first objective in this study was to develop a methodology for estimating displacement factors for primary wood products. Many different products can provide the same service, and the competition of wood products with other types of products creates a number of potential substitution effects involving the forest products industry. For example, consider a single-family home, and comparison of emissions for two functionally equivalent buildings: a more wood-intensive building would use wood-framing, and a less wood-intensive building would use concrete-framing (Gustavsson *et al.*, 2006). In recent decades, the substitution impacts for housing construction has been especially well studied, but with varying results depending on the assumptions on forest C, and end-of-life options (Upton *et al.*, 2008). Gustavsson *et al.* (2006) found that the production of wood-framed buildings in Scandinavian countries emits less than the production of functionally equal concrete-framed buildings. A meta-analysis of 21 studies by Sathre & O'Connor (2010) calculated displacement factors ranged from a low of −2.3 to a high of 15.0 (tonnes of carbon of emission reduction per tonne of carbon used in wood product) with an average value of 2.1. The variability in displacement factors occurred because they considered a variety of end-use products and a variety of system definitions. Nonetheless, their average value of 2.1 has been used in other studies (e.g. Malmsheimer *et al.*, 2011; Macintosh *et al.*, 2015), or 1.1 if the biogenic emissions were removed (Keith *et al.*, 2015), or a range of displacement factors has been assumed (Hennigar *et al.*, 2008; Soimakallio *et al.*, 2016). The product displacement factor was estimated to be 1.5 by Knauf *et al.* (2015) for Germany, and their study included 16 estimates of displacement factors, which were volume weighted based on a material flow analysis, and a single substitution factor was obtained. Here we use a similar method to estimate displacement factors for sawnwood and panels for Canada by comparing emissions from functionally equivalent products that are weighted based on the national statistics of the broad uses of wood in Canada.

For substitution benefits from bioenergy products, a number of studies have examined GHG reductions and have found that impacts depend on the feedstock source, conversion efficiency and displaced fossil fuel characteristics (e.g. Lemprière *et al.*, 2013). Bioenergy substitution impacts have been assessed for specific fuel types separately (e.g. Schlamadinger & Marland, 1996; Guest *et al.*, 2012; Zanchi *et al.*, 2012) and for specific regions (Ralevic *et al.*, 2010; McKechnie *et al.*, 2011; Ter-Mikaelian *et al.*, 2011) but there are few national-level studies of fossil fuel displacement (Werner *et al.*, 2010; Whittaker *et al.*, 2011; Lundmark *et al.*, 2014; Smyth *et al.*, 2014), and, to date, no national studies have considered regional fossil fuel and feedstock availability together with optimized choices about bioenergy facilities to maximize substitution benefits. In Canada, substantial regional heterogeneity exists in the feedstock supply and energy demand, and the emissions intensity of future electricity production varies markedly between jurisdictions. Given the substantial variation in energy demand, fibre availability and fossil fuel use, we anticipate large variations in the regional displacement factor.

The second objective of this study was to estimate regional bioenergy displacement factors for local heat and electricity production. Strategic and operational-level decision-making requires consideration of relevant factors that can vary substantially across the country, meaning that decision-making about the objectives and feasibility of forest-based bioenergy must take into account local or regional conditions. In this study, we employed an optimization technique to maximize avoided emissions by selecting (from nine candidate bioenergy facilities) the type, size and number of bioenergy facilities that would displace the highest-emitting fossil fuels with a given supply of harvest residues as feedstock.

In the following section, we introduce the methodologies that were applied consistently across the country to identify and examine the differences generated by local circumstances. These results will be useful for policy-makers considering mitigation portfolios, both at the national level and at the regional level.

Materials and methods

Analytical framework

In this study, product displacement factor calculations included emissions associated with extraction, transportation of raw materials and manufacturing. We assumed that the emissions associated with transporting the finished products to the consumer were the same for wood and nonwood products and did not therefore include these estimates.

For energy displacement factors, we constrained bioenergy production to be local, within a forest management unit (FMU), of which we include 634 in Canada's managed forest that are similar to the spatial analysis units used by Stinson *et al.* (2011, Fig. 1). Conversion efficiencies for nine selected

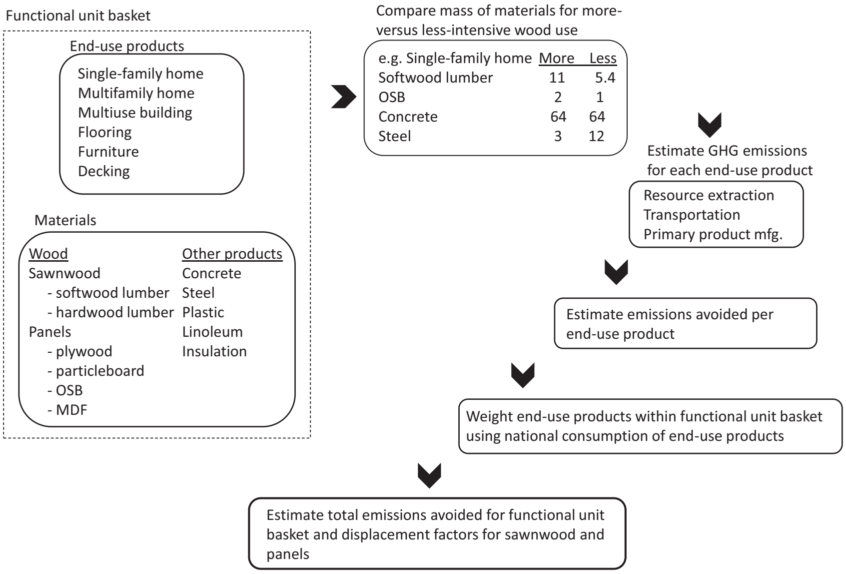

Fig. 1 Overview of the method for calculating wood product displacement factors.

bioenergy facilities were used to estimate the amount of heat and electricity that could be produced, with assumed complete combustion. We did not include processing emissions associated with grinding and loading of the extracted harvest residues or transportation emissions because we assumed these emissions to be minimal relative to the combustion emissions (Jones *et al.*, 2010). Avoided fossil fuel emissions were based on published emissions intensities that included extraction, transportation of raw materials and conversion to heat or electricity.

Greenhouse gas emissions and removals associated with forest ecosystem C dynamics, emissions from instant oxidation of bioenergy and release of C from the processing of HWPs and from postconsumer emissions were not included in this analysis because they were addressed in other system components (Smyth *et al.*, 2016). Displacement factors estimated here are used to estimate the avoided emissions per unit of wood used. They can only be used within the larger system framework and must not be used in isolation as such use would fail to account the impacts of harvesting on ecosystem C balances and the emissions from HWPs.

Product substitution

Sawnwood and panels are traditionally used to manufacture a variety of end-use products, each with a different GHG implication. Displacement factors for sawnwood and panels were determined by considering a basket of end-use products. We have defined each end-use product as a functional unit, which describes the service delivered by the product (e.g. single-family home). For each functional unit, a comparison of GHG emissions based on the construction materials for two functionally equivalent products was estimated. Each end-use product was then weighted based on national consumption statistics to ensure that the basket reflected national usage. Finally, displacement factors were estimated for sawnwood and panels, the main wood commodities contained in the end-use products. The overall process is described in the schematic in Fig. 1.

The basket of end-use products included buildings (single-family home, multifamily home, six-storey multiuse building), residential flooring, furniture and decking. The amount of wood and other materials needed for each end-use product was estimated for a more wood-intensive product, relative to a less wood-intensive product. Operational emissions for buildings can account for the majority of GHG emissions (Sharma *et al.*, 2011), but estimating these emissions was beyond the scope of this study, and we assumed that the end-use products for both scenarios would have the same operational functional life and operational emissions and that differences in emissions between the scenarios were solely the result of material selection and construction. We further assumed that all solid wood products had the same specific gravity.

Materials' emissions factors were taken from published values for each end-use product (Schmidt *et al.*, 2004, Marceau *et al.*, 2007; Athena Sustainable Materials Institute, 2008a,b, 2009a,b,c; National Renewable Energy Laboratory, 2008, Bala *et al.*, 2010). We preferentially selected material lists and emissions factors for end-use products manufactured within North America, where available, to ensure consistency between end-use products and national consumption statistics.

For each end-use product, f, the net emissions avoided, N_f, for a more wood-intensive product relative to a less wood-intensive product was estimated as:

$$N_f = \sum_{i=1}^{n} \Delta m_i (x + t + s)_i, \qquad (1)$$

where n is the total number of materials in each end-use product; Δm is the difference in mass of a material for (more wood-intensive minus less wood-intensive) for the two comparative products; and x, t and s are emissions for resource extraction, transportation and primary product manufacturing, respectively.

A weighting factor, W_f, was applied to weight each end-use product's avoided emissions within the functional unit basket. It was estimated from the proportion of wood consumed at the national level for each broad wood use (buildings, residential improvement, furniture and manufacturing) divided by the proportion of wood within the functional unit basket. The weighting factor for each end-use product was defined as:

$$W_f = \frac{A_f}{m_{Mf}/\sum_{f=1}^{6} m_{Mf}}, \qquad (2)$$

where A_f is the percentage of the 2005–2010 average annual consumption of primary solid wood products in each end-use product as reported by the Forest Economic Advisors' statistics for Canada (FEA, 2011), and m_{Mf} is the mass (m) of wood material in the more (M) wood-intensive end-use products.

The weighted avoided emissions were then estimated as:

$$N_{fD} = N_f W_f, \qquad (3)$$

which represented the emissions avoided for each weighted end-use product within the functional unit basket weighted by national consumption levels.

Displacement factors were estimated for each primary solid wood product, p (representing sawnwood and panels) based on the percentage of primary products reported by FEA for Canada within each of the six end-use products (K_{fp}) in the functional unit basket:

$$\mathrm{DF}_p = \frac{\sum_{f=1}^{6} N_{fD} K_{fp}}{D_p}, \qquad (4)$$

$$D_p = \sum_{f=1}^{6} \Delta M_{fp} W_f, \qquad (5)$$

where the total avoided emissions per basket for each functional unit component were converted to total avoided emissions for sawnwood and panels by weighting N_{fD} using the shares of sawnwood and panels in each functional unit component, respectively. Then, the weighted avoided emissions for sawnwood and panels were divided by the incremental increase in wood mass, D_p, for those two products, respectively, to calculate the displacement factors. The final values were converted from $\mathrm{tCO_2\ t^{-1}}$ wood to $\mathrm{tC\ tC^{-1}}$. We did not partition the displacement factor for panels into nonstructural and structural components because of the HWP commodity tracking framework uses an aggregated half-life for structural and nonstructural panels (Smyth *et al.*, 2014).

Energy substitution

Substitution emissions from using bioenergy (bioenergy scenario) in place of fossil fuels (business-as-usual scenario) were estimated by comparing fossil fuel emissions to bioenergy emissions for combinations of nine bioenergy facilities, based on an assumption that bioenergy would substitute for the most emission-intensive fuel source first, and then proceed to successively less emission-intensive fuels. An overview of the process is shown in the schematic in Fig. 2. A linear programming (LP) model was created to determine the optimal configuration (type, size and number) of regional bioenergy facilities that maximized avoided emissions. Regions were defined based on 502 FMUs in which harvesting and silvicultural activities are undertaken (Stinson *et al.*, 2011) and for which mitigation estimates are projected (Smyth *et al.*, 2016).

Energy demand for heat and electricity combined within each region was estimated from each jurisdiction's per capita energy (heat and electricity) usage (National Energy Board, 2013) multiplied by the region's population. We assumed that one-third of the energy usage was for electricity and two-thirds for heat (National Energy Board, 2010). Population within a region was estimated from census data (Statistics Canada, 2011) by overlaying the FMU boundaries with population dissemination blocks. These blocks are the smallest geographic area for which population and dwelling counts are disseminated.

Fossil fuel sources for electricity production were based on the projected fuel mix for each jurisdiction (National Energy Board, 2013) averaged over the period 2017–2035. Fossil fuel sources for heat production were based on contemporary estimates of heat fuel sources were used (Office of Energy Efficiency, 2015) because projections were unavailable. Each jurisdiction's energy use was compiled by fuel type for space heating in the residential and commercial sector, and process heating for the industrial sector. There were limited data available on process heat, and the fuel mix without electricity was used as a proxy of the energy mix for heat. When electricity was excluded, over 90% of industrial energy was used for process heating (boilers or heaters) (National Energy Board, 2013).

Each FMU was assumed to have the average fuel mix for electricity and heat of the province or territory. However, some FMUs contain remote (off-grid) communities with a different fuel mix (Natural Resources Canada, 2015). In such instances, the FMU-level fuel mix was adjusted to reflect remote communities' fuel usage, based on the relative population sizes of the remote communities and the FMU.

Fossil fuel emissions intensities were taken from published values (Office of Energy Efficiency, 2015). Heat generated from electricity was assumed to use the average grid emissions intensity. We assumed that only fossil fuels would be displaced, and therefore, it was not necessary to quantify emissions for nuclear, hydro-electricity, wind, tide and existing biomass energy sources. Emissions intensities for electricity were highest for coal at 1 $\mathrm{tCO_2e\ MWh^{-1}}$, followed by fuel oil and diesel at 0.8 $\mathrm{tCO_2e\ MWh^{-1}}$ and natural gas as 0.45 $\mathrm{tCO_2e\ MWh^{-1}}$. Heating fuel emissions ranged from 0.438 $\mathrm{tCO_2e\ MWh^{-1}}$ for coal and petcoke, to 0.361 $\mathrm{tCO_2e\ MWh^{-1}}$ for fuel oil, and 0.255 $\mathrm{tCO_2e\ MWh^{-1}}$ for natural gas. Heat emissions from electricity were based on the fuel mix for electricity within a given jurisdiction and ranged from 0.0012 to 0.585 $\mathrm{tCO_2e\ MWh^{-1}}$ (Table S2).

For the bioenergy facilities, nine facilities were selected from the literature as representative of potential installations applicable to variety of Canadian regions and for which information was available on emissions and costs (Pröll *et al.*, 2011, Wood & Rowley, 2011; Biopathways, 2012, RETScreen International, 2015). The nine selected bioenergy facilities had a range of

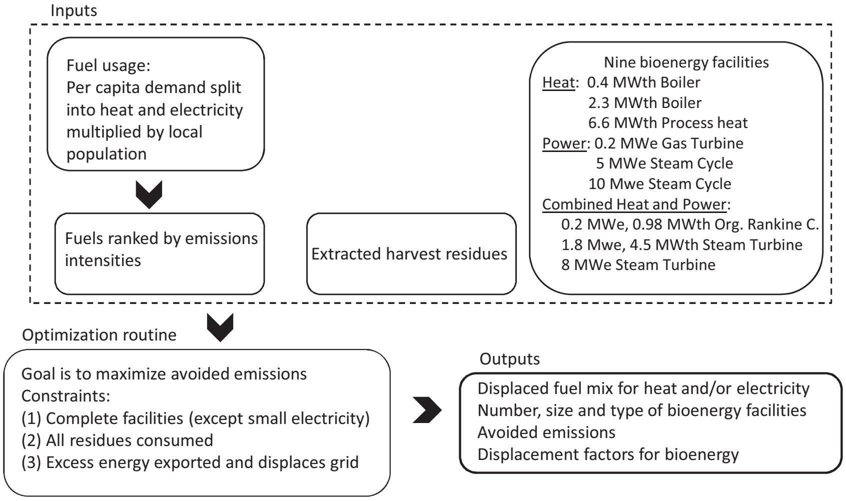

Fig. 2 Overview of the method for calculating bioenergy displacement factors. Transportation emissions associated with transport of residues were not included.

200–400 kW for small facilities, and 7–10 MW for large facilities (Table 5). Biomass demand for the facilities ranged from 0.8 to 2 kodt yr^{-1} for small facilities, and for large facilities biomass demand ranged from 47 to 64 kodt yr^{-1}. Energy facilities included boilers for district and process heat production, and steam and gas turbines for CHP and power production. The functional units for energy were 1 MWh of electricity and 1 MWh of heat.

The LP model maximized avoided emissions, E_a,

$$E_a = \max\left(\sum H_j I_j + \sum V_k I_k\right), \tag{6}$$

where H and V are the amounts of energy (in MWh) produced by each fuel that would be displaced by harvest residues used in heat and electricity production, respectively; I is the emissions intensity for j = 4 heat fuels: (1) coal and petcoke, (2) fuel oil, (3) natural gas and (4) electricity; and k = 5 electricity fuels: (1) coal, (2) fuel oil, (3) diesel, (4) natural gas and (5) grid. LP model inputs were the extracted harvest residues, regional energy demand, and existing fuel sources and emissions intensities for heat and electricity production. We assumed that all extracted harvest residues would be used to generate energy locally, within the FMU. We did not include raw material transportation emissions, and these would likely vary across the FMUs given the differences in FMU sizes. The total amount of energy that could be substituted was constrained by the amount of extracted harvest residues within each FMU, and only complete facilities were permitted except in the case of the small electricity facility where partial facilities were permitted to ensure all residues were consumed. Heat production was constrained by the local heat demand. If the amount of bioenergy produced exceeded local demand, then excess biomass was converted to electricity and exported to the electricity grid.

A bioenergy displacement factor, DF$_e$ (tC avoided per tC used), was estimated for each region as the total maximum avoided emissions divided by the C in extracted harvest residues:

$$\mathrm{DF_e} = E_a\left(\frac{12}{44}\right)R^{-1}, \tag{7}$$

where E_a is the avoided emissions in tCO$_2$e, R is the C in extracted harvest residues in tC, and the factor of 12/44 converts from CO$_2$ to C.

Two examples were selected to estimate the range in displacement factors within the optimization results. In the first example, *constant supply*, displacement factors for each FMU were estimated for a fixed biomass feedstock of 64 thousand oven-dried tonnes (kodt), which matched the fibre demand of the largest electricity facility or six medium CHP facilities. In the second example, *constrained supply*, extracted harvest residues were limited to meet each FMU's actual demand for heat from fossil fuels to (1) assess the change in displacement factors relative to a *constant supply* example and to (2) determine the amount of extracted harvest residues needed to displace fossil fuel based heat production. We included heat produced from electricity as fossil fuel based heat if the grid emissions exceeded 400 kg CO$_2$e MWh^{-1}. If the residues available in the *constrained supply* case could not support a small heat facility locally, we did not estimate a displacement factor in that FMU.

Results

Wood product substitution

Table 1 shows the six end-use products compiled from the literature that were selected for the functional unit basket, and their associated material uses for a more wood-intensive scenarios as compared to a less wood-intensive scenario. The comparative material lists showed that sawnwood predominantly substituted for steel in single-family homes, sawnwood substituted for concrete in multifamily homes, and sawnwood and

Table 1 The composition and associated material mass (in tonnes) of the six comparative end-use products for the functional unit basket

End-use product	Material	Mass more wood-intensive (t)	Mass less wood-intensive (t)
Single-family home*	Sawnwood (softwood lumber)	10.8	5.4
	Panel: Oriented Strand Board (OSB)	2.2	1.1
	Concrete	63.5	64.0
	Steel Beams	3.0	11.6
Multifamily home†	Sawnwood (softwood lumber)	59.0	33.0
	Panel: Particleboard	18.0	17.0
	Panel: Plywood	21.0	20.0
	Concrete	223	1352
	Steel Beams	16.0	25.0
	Insulation	21.0	25.0
Multiuse building‡	Sawnwood (softwood lumber)	75.0	0.0
	Panel: Particleboard	17.0	3.0
	Panel: Plywood	21.0	0.0
	Concrete	236	1430
	Steel Beams	550	703
Flooring§ (Residential upkeep)	Sawnwood	0.7	0.077
	Linoleum	0	0.18
Furniture¶	Panel: Medium Density Fibreboard	0.011	0
	Plastic [High-density polyethylene (HDPE)]	0	0.0034
Decking‖ (Manufacturing)	Sawnwood (softwood lumber)	0.36	0
	Plastic (HDPE)	0	0.21
	Wood flour (saw dust)	0	0.05

*A typical two-storey house in Minneapolis with a basement and total floor area of 192 m^2. Design consisted of solid wood-framing members except for composite floor I-joists, OSB sheathing for roof, walls and floor, and pre-engineered roof trusses (Lippke *et al.*, 2004).

†Four-storey building with 16 apartments with a floor area of 1190 m^2 (Gustavsson *et al.*, 2006).

‡A 7300 m^2, six-storey university building. The bottom three floors and basement are used as classrooms and open-plan offices, the top three floors are used as hotel rooms (Scheuer *et al.*, 2003).

§100 m^2 of flooring (Nedermark, 1998).

¶TV chassis (Beovision Avant) (Jönsson *et al.*, 1997).

‖Deck surface (29.7 m^2) assuming a 10-year service life.

panels substituted for steel and concrete in multiuse buildings. For the other three end-use products (flooring, furniture and decking), sawnwood and panels replaced plastic in the comparison studies selected.

Estimates of GHG material emissions (Table 2) were compiled from published studies, with preference given to North American products and uses. For solid wood products, lumber (sawnwood) and plywood have lower unit emissions than particleboard, Oriented Strand Board and Medium Density Fibreboard (MDF), due to the higher manufacturing and transportation emissions.

Based on the published comparative studies for the six end-use products, multiuse buildings had the highest avoided emissions (Table 3) mainly due to the substitution of wood for large amounts of steel and concrete. Multifamily home and single-family home components also had steel and concrete substitution, but avoided emissions were lower than in multiuse buildings because of the lower material demands. The avoided emissions for manufacturing (decking in our analysis) were small, as were the avoided emissions for residential upkeep. Furniture avoided emissions, represented as MDF vs. HDPE plastic, were found to have small negative avoided emissions, indicating the use of fibreboard increased emissions relative to plastic for the selected comparative study due to its higher emission intensity (Table 2).

National consumption statistics were used to partition sawnwood and panels within the six end-use products. Sawnwood was primarily used in residential upkeep (represented by flooring in this analysis) at 35% of the total, manufacturing (represented by decking) at 27% and single-family homes at 16% (Table 3). Panels were used in most end-use products, but had modest volume percentages that ranged from 1% to 4%.

Table 2 Greenhouse gas emissions for materials used in the functional unit basket

Primary product	Total (kg CO_2e t^{-1})	x Extraction (kg CO_2e t^{-1})	t Transportation (kg CO_2e t^{-1})	s Manufacturing (kg CO_2e t^{-1})
Lumber*	111.8	32.7	17.9	61.3
MDF†	2646	62.2	159.8	2424
OSB‡	586	82.0	51.5	452
Particleboard§	1191	41.6	98.8	1050.4
Plywood¶	240.3	53.5	28.0	158.9
Concrete‖	88.0	0.8	2.3	84.9
Steel (from ore)**	2797	1180	30.0	1587
Insulation††	214.0	214.0	0	0
Linoleum flooring‡‡	608.8	0.0	0.0	608.8
High-density polyethylene§§	1800	0.0	0.0	1800

MDF, Medium Density Fibreboard; OSB, Oriented Strand Board.
*Based on 2.3597 m^3 (thousand board feet) (Athena Sustainable Materials Institute 2009c).
†Based on 92.903 m^3, 19 mm basis (thousand square feet, 3/4 inch basis) (Athena Sustainable Materials Institute 2009a).
‡Based on 92.903 m^3, 9.5 mm basis (thousand square feet, 3/8 inch basis) (Athena Sustainable Materials Institute 2008a).
§Based on 92.903 m^3, 19 mm basis (thousand square feet, 3/4 inch basis) (Athena Sustainable Materials Institute 2009b).
¶based on 92.903 m^3, 9.5 mm basis (thousand square feet, 3/8 inch basis) (Athena Sustainable Materials Institute 2008b).
‖Marceau *et al.* (2007).
**National Renewable Energy Laboratory (2008) and Iosif *et al.* (2010).
††Schmidt *et al.* (2004).
‡‡Based on 100 m^2 (Jönsson *et al.*, 1997).
§§Bala *et al.* (2010).

Table 3 End-use product avoided emissions, Canadian consumption statistics and weighting factors

End-use product	N_f Avoided emissions (tCO_2 per end-use product)	A_f Canadian wood consumption (% volume, sawnwood, structural panels, nonstructural panels)	m_{MF} Mass of wood material in the more wood-intensive end-use product (t)	W_f Weighting factor
Single-family home	22.8	19.0 (15.8, 3.3, 0.1)	13	3.3
Multifamily home	121.1	5.3 (3.6, 1.6, 0.1)	98	0.12
Multiuse building	503.0	4.0 (3.0, 0.8, 0.1)	113	0.08
Flooring (residential upkeep)	0.03	39.7 (35.1, 3.4, 0.8)	0.74	121
Furniture	−0.02	3.2 (0, 0, 3.2)	0.011	662
Decking (manufacturing)	0.3	28.8 (27.2, 1.9, 0)	0.36	180

Weighting factors estimated for each end-use product within the functional unit basket ranged from 0.1 to 662 (Table 3). These weighting factors were applied to the mass of wood in each end-use product, to estimate the total avoided emissions for each end-use product in the functional unit basket (Table 4). The highest avoided emissions for end-use products weighted by national consumption were for single-family homes (75 tCO_2 per home), manufacturing (62 tCO_2 per deck) and multiuse buildings (40 tCO_2 per building).

Partitioning the avoided emissions into sawnwood and panels found that overall displacement factor for sawnwood was 0.99 tCO_2 avoided per tonne of sawnwood or 0.54 tC tC^{-1} and for panels the displacement factor was 0.83 tCO_2 avoided per tonne of panels or 0.45 tC tC^{-1}.

Bioenergy substitution

Nine bioenergy facilities (Table 5) included three facilities for heat production, three for electricity production and three for combined heat and power production. Energy demand and fuel mix (projected electricity and contemporary heat) varied substantially across the

Table 4 Weighted avoided emissions by end-use product and proportion of sawnwood and panels in the incremental change in mass for more-intensive vs. less-intensive end-use products

End-use product	N_{fD} Weighted Avoided Emissions in the basket (tCO_2 per end -use product)	Per cent of incremental wood change (K_{fp})		
		Sawnwood (%)	Structural panels (%)	Nonstructural panels (%)
Single-family home	75.1	83	17	0
Multifamily home	14.8	93	4	4
Multiuse building	39.8	68	19	13
Flooring (residential upkeep)	4.2	100	0	0
Furniture	−15.1	0	0	100
Decking (manufacturing)	62.3	100	0	0

Table 5 Description of the three sizes (small, medium, large) of three types (district heat, power and combined heat and power) for the nine selected bioenergy facilities. Assuming 340 operating days, 24 h per day operating hours and a wood energy content of 20 GJ odt^{-1}

Facility type	Facility description	Biomass demand (kodt yr^{-1})	Electrical conversion rate (MWh odt^{-1})	Thermal conversion rate (GJ odt^{-1})	Assumed electrical efficiency (%)	Assumed thermal efficiency (%)	Implied overall efficiency (%)
Heat	0.4 MWth boiler for district heating*	0.783	–	15.0	–	75	75
	2.3 MWth boiler for district heating†	3.97	–	17.0	–	85	85
	6.62 MWth process heat via syngas‡	11.58	–	16.8	–	84	84
Power	0.2 MWe gas turbine§	1.60	1.02	–	18	–	18
	5 MWe steam cycle‡	34.97	1.17	–	21	–	21
	10 MWe steam cycle‡	63.86	1.28	–	23	–	23
CHP	0.2 MWe, 0.98 MWth Organic Rankine Cycle¶	2.09	0.78	14.0	14	70	84
	1.8 MWe and 4.5 MWth steam turbine‖	10.58	1.39	10.8	25	54	79
	8 MWe CHP steam turbine‡	46.87	1.39	5.88	25	29	54

*Retscreen International (2015).
†Retscreen International (2015).
‡Biopathways (2012).
§Arena *et al.* (2010).
¶Wood & Rowley (2011).
‖Pröll *et al.* (2011).

country (Table 6) and reflected many different influences including available resources, population distribution, climate and resource development.

In the first example, *constant supply*, we chose a fixed wood residue supply of 64 kodt yr^{-1}, which could supply a large electricity facility, or six medium CHP facilities to demonstrate that regions with the same amount of harvest residue consumed could have very different avoided emissions. Estimated displacement factors for 502 FMUs (total of 32 Modt biomass feedstock) had an average displacement factor of 0.47 tC tC^{-1} (range of 0.001–1.85 tC tC^{-1}), with a clear S-shaped trend of greater displacement factors with greater populations (Fig. 3a). Produced heat had to be consumed within the FMU and could not exceed demand, while excess electricity could be exported to the grid. Thus, heat consumption increased with population size (Fig. 3b) while energy exports decreased (Fig. 3d). There were two offset S-shape trends, with the second S-shape having higher displacement factors at all population levels.

Table 6 Average provincial or territorial per capita energy consumption and energy fuel mix for projected electricity production (*E*) and heat production (*H*). Percentages have been rounded and may not add to 100%. Additional details can be found in Table S1

Province or Territory	*E*: consumed (MWh per person)	*H*: consumed (MWh per person)	*E*: coal (%)	*E*: fuel oil (%)	*E*: NG* (%)	*E*: rest† (%)	*H*: coal and petcoke (%)	*H*: fuel oil (%)	*H*: NG (%)	*H*: electricity (%)	*H*: biomass (%)
Alberta	33.5	67.1	32		59	9	21	5	68	1	5
British Columbia	27.7	55.5			13	88	5	9	42	8	35
Manitoba	16.2	32.4				100	2	8	64	15	11
New Brunswick	14.8	29.6	16		11	74	3	37	9	32	19
Newfoundland and Labrador	16.3	32.6		1	2	98	1	30	0	44	25
Northwest Territories	30.8	61.6		46	13	41	11	53	11	5	16
Nova Scotia	11.8	23.7	30		34	35	2	69	0	2	28
Ontario	13.0	25.9			19	80	26	5	57	4	8
Prince Edward Island	12.4	24.8				100	4	50	5	16	25
Quebec	15.1	30.2			2	99	10	13	34	19	24
Saskatchewan	33.4	66.9	33		43	23	14	7	70	3	6
Yukon	10.8	21.6		19		81	11	53	11	5	16

*Natural Gas (NG).

†'Rest' includes power generation from hydro-electricity, wind and tide, biomass and uranium.

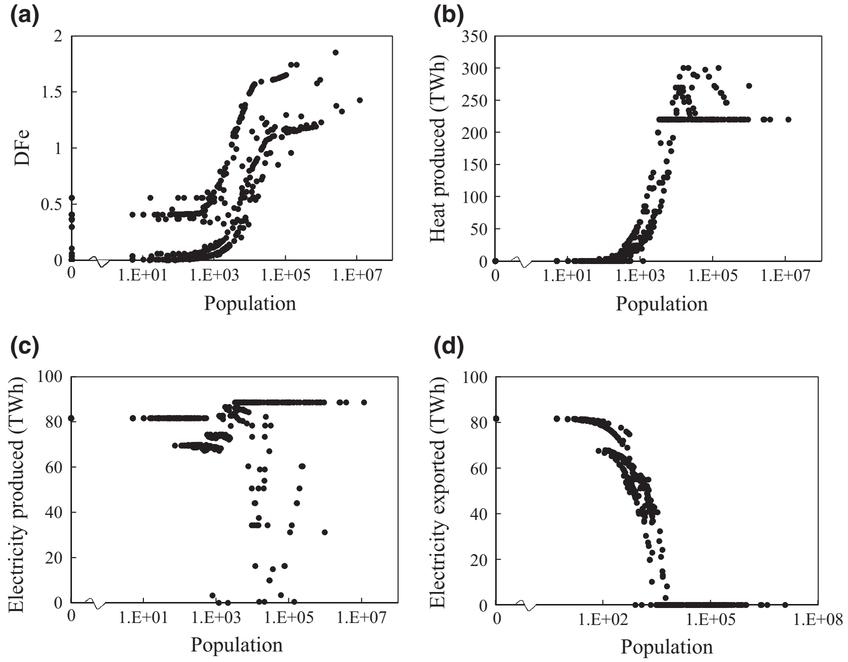

Fig. 3 Displacement factors, annual heat and electricity production, and exported electricity as a function of population within each of the 502 forest management units, assuming a constant annual biomass feedstock of 64 kodt yr^{-1}.

These higher displacement factors were associated with high grid emissions intensities for some regions. Figure 3c shows the electricity produced had three distinct levels of electricity production related to (1) a large electricity facility selected within low population regions, (2) a mix of heat, electricity and CHP facilities in midrange population regions and (3) the highest electricity production associated with six medium CHP facilities in high population regions. For the same amount of feedstock, the six medium CHP facilities produced 220 TWh yr^{-1} of heat as well as more electricity than a large electricity facility due to higher conversion efficiency.

In the second example, *constrained supply*, the amount of bioenergy feedstock was reduced by limiting extracted harvest residues to match the demand of fossil fuel-based heat. The total extracted harvest residues fell to 11.0 Modt and residues were collected in 327 of the 502 FMUs. Heat generated from bioenergy was used to displace heat generated from fuel oil, natural gas and coke and petcoke (Fig. 4a). Electricity was predominantly generated by CHP facilities and displaced electricity generated from natural gas and coal. There was a much smaller proportion of electricity grid than in the *constant supply* example. A minor proportion of wood biomass used for heat production was displaced in the constant supply because all fossil fuel sources had been consumed, but substitution of wood biomass did not contribute to avoided emissions. The average displacement factor was 0.89 in the *constrained supply* example, almost twice as high as in the *constant supply* example (Fig. 4b). Avoided emissions in the *constrained supply* example were equivalent to 80% of the avoided emissions in the *constant supply* example while consuming only 34% of the biomass residues.

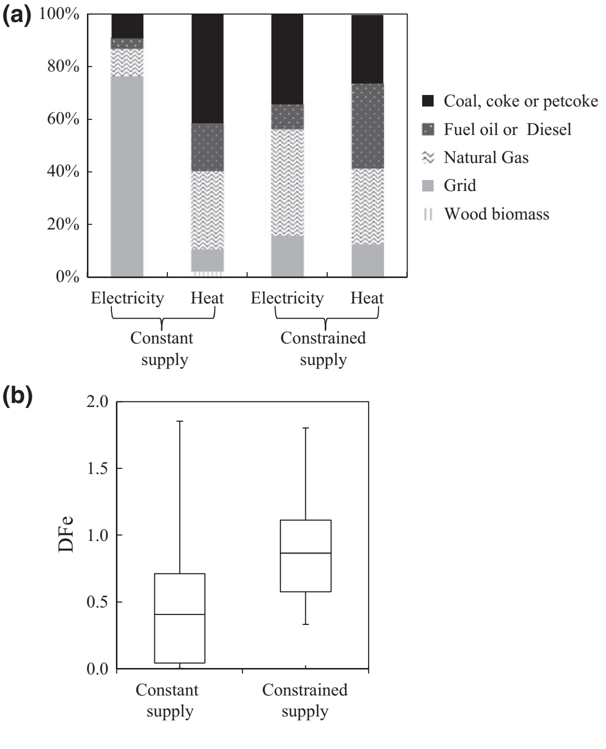

Fig. 4 Comparison of (a) displaced fuel sources percentages for heat and electricity for the *constant supply* example and *constrained supply* example. (b) Boxplots of displacement factors for the two examples with first, third and median values indicated by the boxes, and minima and maxima represented by error bars.

Discussion

The carbon neutrality assumption for bioenergy that forest bioenergy emits no C to the atmosphere as long as the postharvest forest regrows to its preharvest C level fails to properly assess the GHG emissions of bioenergy (Johnson *et al.*, 2009; Ter-Mikaelian *et al.*, 2015). The potential GHG emission reductions that can be achieved through wood use need to be quantified in a systems approach which includes changes in forest C, HWPs tracking and substitution benefits to prevent the development of policies that develop no net benefit to the atmosphere. For product substitution, climate benefits occur in a different sector because emission reductions would occur in manufacturing and transportation sectors due to the reduction in steel or concrete, or plastic production. Policies generally do not include substitution impacts directly, but instead include reductions in overall GHG emissions or promote changes in construction, such as the Wood First Act (BC JTST, 2015).

Product substitution

Wood product displacement factors in this study are lower than the mean displacement factor estimated by Sathre & O'Connor (2010), hereafter S&O. Their meta-analysis estimated an average displacement factor of 2.1 tC tC^{-1} based on 21 studies with considerable range in estimates (−2.3 to 15 tC tC^{-1}), but most factors were between 1 and 3 tC tC^{-1}. There are differences in methodology between this study and S&O which prevent direct comparison. In S&O, the system boundaries were not the same for all studies, with some studies including forest ecosystem emissions, some including operational emissions, as well as postconsumer emissions from landfills and fossil fuels substitution. In this study, we examined product substitution for harvesting, transportation of raw materials and manufacturing, and tracked changes in forest ecosystem emissions and HWP commodity lifetimes and postconsumer treatment in other system components. We estimated displacement factors from four of the studies included by S&O that had the same end-use products as our study (Petersen & Solberg, 2004; Gustavsson *et al.*, 2006; John *et al.*, 2009; Salazar & Meil, 2009). To ensure the system boundaries were the same, we removed the forest ecosystem, operational and postconsumer emissions from the four selected studies and weighted the avoided emissions per end-use product. We found that S&O's displacement factors were 0.51 tC tC^{-1} for sawnwood and 0.14 tC tC^{-1} for panels. These compared reasonably well to our estimates of 0.54 tC tC^{-1} sawnwood and 0.45 tC tC^{-1} for panels.

Additional comparative studies and information on end-uses are needed to reduce the uncertainty in the displacement factor estimates. We are constrained by the availability of comparative studies of product end-uses that include complete material information. One of the key areas of uncertainty is the use of solid wood products in residential upkeep and manufacturing, and corresponding comparative studies that identify emissions in a wood-intensive product vs. plastic products. Also, displacement factors for the primary solid wood products are strongly influenced by the building material lists, and additional data estimating 'typical' building (house, apartment building, office building, etc.) composition for all regions in Canada would be an asset. Our end-use categories are quite broad, and as a result, the selection of comparative end-uses is a source of uncertainty.

Energy substitution

In the first example, a constant biomass supply for all regions revealed that the energy demand for the FMUs was highly variable and that displacement factors generally increased with population due to an increased heat production and decreased export of electricity outside of the FMU. Displacement factors for the same biomass supply and population varied by up to ~0.5, which reflected the different emissions intensities of the jurisdictions' projected electricity fuel sources (Table S2).

In the second example, biomass consumption was reduced so as to only displace heat generated from fossil fuels. Displacement factors increased in this example, but the number of participating regions dropped by almost 35%, and the extracted harvest residues decreased by over 50% relative to other estimates (Smyth *et al.*, 2016). The *constrained supply* example identified regions where local bioenergy production from extracted harvest residues could generate the highest substitution benefits from heat and/or CHP facilities, and it would be of interest to use these optimized feedstock levels in national-level mitigation analyses to assess uncertainty in mitigation estimates.

Our analysis focused on smaller-scale facilities that could support smaller communities, or many facilities could be combined to support cities. We had initially included a 17MWe electricity facility, but this facility could only be supported in a few FMUs with sufficient harvest residues and was never selected by the LP optimization model, so it was replaced by a 10 MWe facility. Adding facilities capable of also utilizing agricultural residues could change the potential facility scale. As noted by Cleary & Caspersen (2015), large electricity facilities may not be as useful as CHP facilities because large electricity facilities are generally not located near population centres, so the heat that is produced cannot be used, and although potentially more efficient, large facilities tend to require additional pelletization processing and larger feedstock transportation distances which offsets increased efficiency.

Our results are consistent with McKechnie *et al.* (2011) who found displaced emissions were higher when harvest residues displaced a high GHG intensity fuel (coal in cofiring) rather than a lower GHG intensity fuel (ethanol in their case, natural gas in ours). Other studies (Guest *et al.*, 2012; Zanchi *et al.*, 2012; Cintas *et al.*, 2015; Cleary & Caspersen, 2015) have also found the magnitude of the displaced emissions depends critically on which fuel source is displaced. Most of the above-mentioned studies focus on electrical systems, but the type of energy produced is also a critical factor and explains why heat is often a better substitution than electricity. This analysis is unique because we considered local use of bioenergy within FMUs for the managed forest of Canada and included remote community fuel usage in the projections of electricity fuel mix.

Two assumptions, (1) the omission of transportation-related emissions for bioenergy and (2) the calculation of avoided emissions from fossil fuels based on current emissions intensities and fixed fuel cost effects, result in an overestimate of the mitigation potential. In the first case, emissions associated with transporting harvest residues to the bioenergy facilities within an FMU were not included. In this study, the transportation emissions are assumed to be small, an assumption that has been in other studies where fixed haul distances or circular transportation distances are assumed (Thakur *et al.*, 2014; Laganière *et al.*, 2015). When short haul distances (<150 km) are used, the emissions associated with transportation are a small percentage of the total emissions from harvesting, transportation and combustion. For example, Jones *et al.* (2010) that emissions from the entire biomass delivery process of collecting, grinding and hauling biomass comprised only 3.2–3.9% of the total emissions, and Domke *et al.* (2012) found that transportation emissions were less than 2% of the total emissions. Transportation costs are often the limiting factor for residue capture, and thus, costs associated with hauling biomass are included in economic modelling (e.g. review by Shabani *et al.*, 2013). It is beyond the scope of the present analysis to estimate transportation-related emissions, but their omission overestimates the mitigation potential if transportation emissions of wood exceed those of fossil fuels. In the second case, we assumed bioenergy would displace the most emissions-intensive fossil fuels without consideration of policies that would target particular fuel types (e.g. closing coal facilities or reducing diesel use). If regions with high-intensity fossil fuels switched to lower emissions fossil fuels, the bioenergy mitigation potential would be overestimated. Further, we did not consider nonfossil fuels in the substitution impacts, but it is possible that bioenergy could be used to substitute for photovoltaics or hydro-electricity, in which case the substitution impacts would be overestimated.

Estimated average displacement factors ranged from 0.47 to 0.89 tC tC^{-1}, with a maximum value of 1.85 tC tC^{-1}. These values are similar to the value of 0.97 tC tC^{-1} by Gan & Smith (2006) for electricity generation from harvest residues and snags displacing coal. More recently, Rajagopal & Plevin (2013) using an economic model suggested that globally the displacement factor varies from 0.4 to 1.0 tC tC^{-1} for ethanol and oil-based transportation fuels.

We did not consider changes in per capita fuel usage over time, nor did we consider changes in population. A potential source of uncertainty is that the energy demand (including industrial energy demand) was assumed to be correlated to population, but industrial facilities can be large consumers not necessarily linked to population centres. Additionally, only local use of bioenergy was considered, and pelletization of residues and export from the FMU was not analysed. Assessing pellet export would require in-depth data on transportation emissions and was beyond the scope of this analysis.

Conclusions

The results of this study highlight the importance of wood use options in mitigating climate change. Forests and forest products can contribute to mitigating climate change, and this analysis presented methods and analyses to estimate substitution benefits from using wood products in the built environment and energy production to displace higher emissions products and fuels at the national level. Wood product substitution benefits should be included when using a systems approach to evaluate mitigation strategy potential, both for domestic and global reductions in GHG emissions. This study examined wood product substitution, and displacement factors from this analysis must be combined with ecosystem and HWP C dynamics to quantify the overall mitigation benefits (e.g. Smyth *et al.*, 2014, 2016).

Displacement factors for solid wood substitution were estimated from a functional unit basket that included three buildings, and three other end-use products for which avoided emissions were weighted by national consumption levels. Displacement factors were found to be 0.54 tC displaced per tC of sawnwood used, and 0.45 tC tC^{-1} for panels.

Displacement factors for bioenergy products were estimated for two feedstock supply levels based on 502 FMUs across Canada, and an optimization routine which displaced highest emissions-intensity fuels in heat, electricity or CHP bioenergy facilities.

Nine bioenergy facilities were selected to represent a variety of energy products (heat, power, CHP), conversion technologies, efficiencies (boilers and turbines) and facility sizes (0.2–10 MW). Displacement factors for a *constant supply* for each region had an average of 0.47 tC tC^{-1} and displaced mostly electricity grid and coal for heat production with 27 $MtCO_2e$ yr^{-1} displaced from 32 Modt yr^{-1} consumed. Displacement factors for feedstock supply that was constrained to meet fossil fuel heat demand had a higher average value of 0.89 tC tC^{-1} and avoided fossil fuel emissions of 22 $MtCO_2e$ from 11 Modt yr^{-1} harvest residues consumed.

Acknowledgements

This study would not have been possible without strong cooperation between provincial, territorial and federal government agencies. We thank all members (past and present) of the National Forest Sinks Committee and their colleagues. Funding for this study was provided by the Government of Canada's Clean Air Agenda, the Program of Energy Research and Development, and in-kind contributions from provincial and territorial governments. We thank our colleague Élizabeth Walsh for her help in compiling energy data, and we thank the anonymous reviewers for their insightful comments.

References

Arena U, Di Gregorio F, Santonastasi M (2010) A techno-economic comparison between two design configurations for a small scale, biomass-to-energy gasification based system. *Chemical Engineering Journal*, **162**, 580–590.

Athena Sustainable Materials Institute (2008a) *A Cradle-to-gate Life Cycle Assessment of Canadian Oriented Strand Board*, pp. 87. Athena Sustainable Materials Institute, Ottawa, ON.

Athena Sustainable Materials Institute (2008b) *A Cradle-to-gate Life Cycle Assessment of Canadian Softwood Plywood Sheathing*, pp. 86. Athena Sustainable Materials Institute, Ottawa, ON.

Athena Sustainable Materials Institute (2009a) *A Cradle-to-gate Life Cycle Assessment of Canadian Medium Density Fiberboard (MDF)*, pp. 95. Athena Sustainable Materials Institute, Ottawa, ON.

Athena Sustainable Materials Institute (2009b) *A Cradle-to-gate Life Cycle Assessment of Canadian Particleboard*, pp. 93. Athena Sustainable Materials Institute, Ottawa, ON.

Athena Sustainable Materials Institute (2009c) *A Cradle-to-gate Life Cycle Assessment of Canadian Softwood Lumber*, pp. 143. Athena Sustainable Materials Institute, Ottawa, ON.

Bala A, Raugei M, Benveniste G, Gazulla C, Fullana-I-Palmer P (2010) Simplified tools for global warming potential evaluation: when 'good enough' is best. *The International Journal of Life Cycle Assessment*, **15**, 489–498.

BC JTST (2015) Wood first initiative: wood first act, ministry of jobs tourism and skills training and responsible for labour. Available at: http://www.bclaws.ca/Recon/document/ID/freeside/00_09018_01 accessed (May, 2016)

Biopathways (2012) Biopathways model. Available at: http://www.nrcan.gc.ca/forests/industry/bioproducts/13321 (accessed May 2012).

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

Cintas O, Berndes G, Cowie AL, Egnell G, Holmström H, Ågren GI (2015) The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. *Wiley Interdisciplinary Reviews: Energy and Environment*, **5**, 351–369.

Cleary J, Caspersen JP (2015) Comparing the life cycle impacts of using harvest residue as feedstock for small- and large-scale bioenergy systems (part I). *Energy*, **88**, 917–926.

Domke GM, Becker DR, D'amato AW, Ek AR, Woodall CW (2012) Carbon emissions associated with the procurement and utilization of forest harvest residues for energy, northern Minnesota, USA. *Biomass and Bioenergy*, **36**, 141–150.

FEA (2011) Forest economic advisors LLC, Quarterly Lumber Forecast Service. Availabe at: https://www.getfea.com/lumber/quarterly-forecast-service/forecast-summary (accessed February 2011).

Gan J, Smith CT (2006) Availability of logging residues and potential for electricity production and carbon displacement in the USA. *Biomass and Bioenergy*, **30**, 1011–1020.

Guest G, Cherubini F, Strømman AH (2012) Climate impact potential of utilizing forest residues for bioenergy in Norway. *Mitigation and Adaptation Strategies for Global Change*, **11**, 667–691.

Gustavsson L, Pingoud K, Sathre R (2006) Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. *Mitigation and Adaptation Strategies for Global Change*, **11**, 667–691.

Hennigar CR, Maclean DA, Amos-Binks LJ (2008) A novel approach to optimize management strategies for carbon stored in both forests and wood products. *Forest Ecology and Management*, **256**, 786–797.

Iosif A-M, Hanrot F, Birat J-P, Ablitzer D (2010) Physicochemical modelling of the classical steelmaking route for life cycle inventory analysis. *The International Journal of Life Cycle Assessment*, **15**, 304–310.

John S, Nebel B, Perez N, Buchanan A (2009) *Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials*. Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand.

Johnson R, Ramseur JL, Gorte RW (2009) *Estimates of Carbon Mitigation Potential from Agricultural and Forestry Activities*. Congressional Research Service.

Jones G, Loeffler D, Calkin D, Chung W (2010) Forest treatment residues for thermal energy compared with disposal by onsite burning: emissions and energy return. *Biomass and Bioenergy*, **34**, 737–746.

Jönsson Å, Tillman AM, Svensson T (1997) Life cycle assessment of flooring materials: case study. *Building and Environment*, **32**, 245–255.

Keith H, Lindenmayer D, Macintosh A, Mackey B (2015) Under what circumstances do wood products from native forests benefit climate change mitigation? *PLoS One*, **10**, e0139640.

Knauf M, Kohl M, Mues V, Olschofsky K, Fruhwald A (2015) Modeling the CO-effects of forest management and wood usage on a regional basis. *Carbon Balance and Managment*, **10**, 13.

Laganière J, Paré D, Thiffault E, Bernier PY (2015) Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy*, **9**, 358–369.

Lemprière TC, Kurz WA, Hogg EH *et al.* (2013) Canadian boreal forests and climate change mitigation. *Environmental Reviews*, **21**, 293–321.

Lippke B, Wilson J, Perez-Garcia J, Bowyer J, Meil J (2004) CORRIM: lifecycle environmental performance of renewable building materials. *Forest Products Journal*, **54**, 8–19.

Lundmark T, Bergh J, Hofer P *et al.* (2014) Potential roles of Swedish forestry in the context of climate change mitigation. *Forests*, **5**, 557–578.

Macintosh A, Keith H, Lindenmayer D (2015) Rethinking forest carbon assessments to account for policy institutions. *Nature Climate Change*, **5**, 946–949.

Malmsheimer RW, Bowyer JL, Fried JS *et al.* (2011) Managing forests because carbon matters: integrating energy, products, and land management policy. *Journal of Forestry*, **109**, S7–S51.

Marceau ML, Nisbet MA, Vangeem MG (2007) *Life Cycle Inventory of Portland Cement Concrete*. Portland Cement Association, Skokie, IL.

McKechnie J, Colombo S, Chen J, Mabee W, Maclean HL (2011) Forest bioenergy or forest Carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, **45**, 789–795.

National Energy Board (2010) Industrial energy use in Canada emerging trends. *Energy Briefing Note*, pp. 21. Calgary, AB. Available at: https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2013/ppndcs/ppndcs-eng.html.

National Energy Board (2013) Canada's energy future 2013 – energy supply and demand projections to 2035 – appendices. Available at: https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2013/ppndcs/ppndcs-eng.html (accessed May 2013).

National Renewable Energy Laboratory (2008) US Life Cycle Inventory Database: hot rolled sheet, steel, at plant. Available at: https://www.lcacommons.gov/nrel/process/show/592324a2-5765-42b5-a5af-f3e6ae87b4ac

Natural Resources Canada (2015) Remote Communities Database. Available at: http://www2.nrcan.gc.ca/eneene/sources/rcd-bce/index.cfm?fuseaction=admin.home1 (accessed May 2014).

Nedermark R (1998) Ecodesign at Bang and Olufsen. In: *Product Innovation and Eco-Efficiency. Twenty-Three Industry Efforts to Reach the Factor 4* (ed. Klostermann J, Tukker A), pp. 233–240. Springer.

Office of Energy Efficiency (2015) Comprehensive Energy Use Database. Available at: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm (accessed May 2015).

Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, **305**, 968–972.

Petersen A, Solberg B (2004) Greenhouse gas emissions and costs over the life cycle of wood and alternative flooring materials. *Climatic Change*, **64**, 143–167.

Pröll T, Rauch R, Aichernig C, Hofbauer H (2011) Fluidized bed steam gasification of solid biomass – performance characteristics of an 8 MWth combined heat and power plant. *International Journal of Chemical Reactor Engineering*, **5**, A54.

Rajagopal D, Plevin RJ (2013) Implications of market-mediated emissions and uncertainty for biofuel policies. *Energy Policy*, **56**, 75–82.

Ralevic P, Ryans M, Cormier D (2010) Assessing forest biomass for bioenergy: operational challenges and cost considerations. *Forestry Chronicle*, **86**, 43–50.

Retscreen International (2015) RETScreen Project Database. Available at: http://www.retscreen.net/ang/software_and_data.php (accessed May 2015).

Salazar J, Meil J (2009) Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. *Journal of Cleaner Production*, **17**, 1563–1571.

Sathre R, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy*, **13**, 104–114.

Scheuer C, Keoleian GA, Reppe P (2003) Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings*, **35**, 1049–1064.

Schlamadinger B, Marland G (1996) The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy*, **10**, 275–300.

Schmidt A, Jensen A, Clausen A, Kamstrup O, Postlethwaite D (2004) A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. *The International Journal of Life Cycle Assessment*, **9**, 122–129.

Shabani N, Akhtari S, Sowlati T (2013) Value chain optimization of forest biomass for bioenergy production: a review. *Renewable and Sustainable Energy Reviews*, **23**, 299–311.

Sharma A, Saxena A, Sethi M, Shree V (2011) Life cycle assessment of buildings: a review. *Renewable and Sustainable Energy Reviews*, **15**, 871–875.

Smyth CE, Stinson G, Neilson E, Lemprière TC, Hafer M, Rampley GJ, Kurz WA (2014) Quantifying the biophysical climate change mitigation potential of Canada's forest sector. *Biogeosciences*, **11**, 3515–3529.

Smyth C, Kurz WA, Rampley GJ, Lemprière TC, Schwab O (2016) Climate change mitigation potential of local use of harvest residues for bioenergy in Canada. *GCB Bioenergy*, **9**, 817–832.

Soimakallio S, Saikku L, Valsta L, Pingoud K (2016) Climate change mitigation challenge for wood utilization – the case of Finland. *Environmental Science & Technology*, **50**, 5127–5134.

Statistics Canada (2011) Dissemination block boundary file. Available at: http://www12.statcan.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm (accessed May 2014).

Stinson G, Kurz WA, Smyth CE *et al.* (2011) An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, **17**, 2227–2244.

Ter-Mikaelian M, Mckechnie J, Colombo S, Chen J, Maclean H (2011) The carbon neutrality assumption for forest bioenergy: a case study for northwestern Ontario. *The Forestry Chronicle*, **87**, 644–652.

Ter-Mikaelian MT, Colombo SJ, Chen J (2015) The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting. *Journal of Forestry*, **113**, 57–68.

Thakur A, Canter CE, Kumar A (2014) Life-cycle energy and emission analysis of power generation from forest biomass. *Applied Energy*, **128**, 246–253.

Upton B, Miner R, Spinney M, Heath LS (2008) The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass and Bioenergy*, **32**, 1–10.

Werner F, Taverna R, Hofer P, Thürig E, Kaufmann E (2010) National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment. *Environmental Science & Policy*, **13**, 72–85.

Whittaker C, Mortimer N, Murphy R, Matthews R (2011) Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass and Bioenergy*, **35**, 4581–4594.

Wood SR, Rowley PN (2011) A techno-economic analysis of small-scale, biomass-fuelled combined heat and power for community housing. *Biomass and Bioenergy*, **35**, 3849–3858.

Zanchi G, Pena N, Bird N (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4**, 761–772.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Electricity fuel mix percentages for combined industrial, commercial and residential consumption.
Table S2. Average electricity grid emissions for projected fossil-fuel sources (National Energy Board, 2013).
Table S3. Displacement factors (DF) for the *Constant Supply* example and the *Constrained Supply* example.