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

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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

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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 (Lempréiere 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
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 as 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. Malmshheimer 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. Leprière 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; Whitaker 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 policymakers 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
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:

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

where $n$ is the total number of materials in each end-use product; $\Delta m_i$ 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, \( W_i \), 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:

\[
W_i = \frac{A_i}{m_{Mf_i}/\sum_{j=1}^{6} m_{Mf_j}}, \tag{2}
\]

where \( A_i \) 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 \( m_{Mf_j} \) is the mass (m) of wood material in the more \( (M) \) wood-intensive end-use products.

The weighted avoided emissions were then estimated as:

\[
N_{DF} = N_{DF} W_i, \tag{3}
\]

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:

\[
D_{fp} = \frac{\sum_{j=1}^{6} N_{DF} K_{fp}}{D_p}, \tag{4}
\]

\[
D_p = \sum_{j=1}^{6} \Delta M_{fp} W_f, \tag{5}
\]

where the total avoided emissions per basket for each functional unit component were converted to total avoided emissions for sawnwood and panels by weighting \( N_{DF} \) 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 \( tCO_2 \, t^{-1} \) wood to \( tC \, t^{-1} \). 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 \( tCO_2 \, MWh^{-1} \), followed by fuel oil and diesel at 0.8 \( tCO_2 \, MWh^{-1} \) and natural gas as 0.45 \( tCO_2 \, MWh^{-1} \). Heating fuel emissions ranged from 0.438 \( tCO_2 \, MWh^{-1} \) for coal and petcoke, to 0.361 \( tCO_2 \, MWh^{-1} \) for fuel oil, and 0.255 \( tCO_2 \, MWh^{-1} \) 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 \( tCO_2 \, MWh^{-1} \) (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 (Proll et al., 2011, Wood & Rowley, 2011; Biopathways, 2012, RETScreen International, 2015). The nine selected bioenergy facilities had a range of
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, $E_a$,

$$E_a = \max \left( \sum H_i I_i + \sum V_i I_i \right),$$

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, $D_{Fe}$, (tC avoided per tC used), was estimated for each region as the total maximum avoided emissions divided by the C in extracted harvest residues:

$$D_{Fe} = \frac{E_a}{12/44} R^{-1},$$

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
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%.

| 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 m². 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 m² (Gustavsson et al., 2006).
‡A 7300 m², 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 m² of flooring (Nedermark, 1998).
¶TV chassis (Beovision Avant) (Jönsson et al., 1997).
||Deck surface (29.7 m²) assuming a 10-year service life.
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

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

| Primary product | Total (kg CO$_2$.t$^{-1}$) | Extraction (kg CO$_2$.t$^{-1}$) | Transportation (kg CO$_2$.t$^{-1}$) | Manufacturing (kg CO$_2$.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).

**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                   |
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 t⁻¹ (range of 0.001–1.85 tC t⁻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 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 | $N_{D}$ Weighted Avoided Emissions in the basket (tCO₂ per end-use product) | Per cent of incremental wood change ($K_{D}$) |
|-----------------|-------------------------------------------------|--------------------------------------------|
|                 | Average 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).
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

### Table 6

| 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 pet coke (%) | 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            | 9                        | 42             | 8         | 35                |               |
| Manitoba              | 16.2                        | 32.4                          | 100         | 2              | 8          | 64           | 15                       | 11             |           |                   |               |
| New Brunswick         | 14.8                        | 29.6                          | 11          | 74             | 3          | 37           | 9                        | 32             | 10        |                   | 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         |                   | 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](image-url) 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.
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 pet coke (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.

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 \textit{et al.}, 2009; Ter-Mikaelian \textit{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 \textit{et al.}, 2006; John \textit{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\(_2\)e 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\(_2\)e from 11 Modt yr\(^{-1}\) harvest residues consumed.

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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.