Supplementary Information

The Carbon Profile of the Managed Forest Sector in Canada in the 20th Century: Sink or Source?

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Journal: Environmental Science and Technology

Date prepared: July 18, 2014

Contents: 34 pages (including this cover page), 1 figure, 9 tables

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CONVERSION FROM INDUSTRIAL ROUNDWOOD TO HARVESTED WOOD PRODUCTS

The amount of industrial roundwood harvested in Canada is often reported in terms of merchantable volume of stem wood. Therefore, to project the amount of carbon in wood products, it is necessary to first estimate the total wood volume harvested, which is based on but differs from the merchantable volume of industrial roundwood[1,2]. This volume is converted to carbon, which is then allocated to various harvested wood products (HWP) types and residue, as described below.

Estimating Total Harvested Wood. Table S1 provides merchantable volume of industrial roundwood harvested in Canada from 1951 to 2010 (harvest volume included for each year starts January 1 and ends December 31). Roundwood statistics in Canada for the period 1951 to 1959 were extracted from Kurz et al.[3]. For the period 1960 to 2010, data were obtained from the database of the Food and Agriculture Organization of the United Nations, FAOSTAT (available from http://faostat.fao.org/site/626/default.aspx#ancor; accessed Jan 15, 2014). Pulpwood

Table S1. Decadal harvest of industrial roundwood in Canada (merchantable volume, million m^3), 1951 to 2010

Category of roundwood	Decade					
	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Logs[§]	338.4	645.4	964.5	1213.8	1482	1446.1
Pulpwood	279.6	370.2	396.7	397.7	300.1	243.8

[§] ‘Logs’ included sawlogs, veneer logs, and wood harvested as ‘other industrial roundwood’.

harvest from 1990 to 2010 was largely not available in FAOSTAT, thus the National Forestry Database of Canada was used (www.nfdp.ccfm.org/products/national_e.php; accessed Jan 15, 2014).

Forest harvest sometimes includes non-merchantable wood, such as undersized wood (e.g., tops, large branches, and non-merchantable trees). We applied expansion factors from Chen et al.[2] to include the non-merchantable wood removed with the merchantable volume (Table S2), and for bark on both merchantable and undersize stems. The resulting total volume of industrial roundwood was then converted to carbon using a factor of 0.25, assuming that, on average, a cubic metre (m^3) of dry wood weighs 0.5 tonne and wood is 50% carbon by mass[4].

Table S2. Bark and undersized expansion factors for timber harvested by Canadian harvested wood product industries by primary wood use (Chen et al.[2])

Use of wood	Lumber and veneer[§]	Pulp and paper	All harvested wood[¶]
Bark expansion	1.127	1.158	1.131
Undersize expansion	1.014	1.107	1.027
Combined expansion	1.143	1.282	1.162

[§] ‘Lumber and veneer’ included wood harvested for lumber and veneer production and wood harvested as ‘other industrial roundwood’.

[¶] Factors for ‘all harvested wood’ are the weighted average values of the two primary wood uses by their fractions in the total wood harvested.

Allocating Harvested Wood Carbon to Products and Residue. Conversion from harvested wood to various HWP and mill residues was simulated using parameters developed by Chen et al.[2]. Despite technological advances, the conversion efficiency in lumber manufacturing, defined as the ratio of industrial roundwood volume to the volume of lumber, was virtually unchanged over the period 1901 to 2010 in North America[5,6]. This can be partially explained by the fact that timber harvest in North America was concentrated on good quality, larger diameter trees before 1950[7]. From 1901 to 1950, the use of mill residue in manufacturing non-structural panel products[8] (i.e., particleboard, medium density fibreboard, hardboard, and insulating board), and in producing energy and pulp chips[9] was very limited in Canada. However, since 1970, significant increases have occurred in all these residue utilization categories[6,9]. Based on the above analysis, we assumed that from 1900 to 1940, sawmill residue was treated as waste. For disposal of this waste, we assumed 50 and 25% of sawmill residue was disposed of in industrial landfills and stockpiles, respectively, and another 25% was burned without energy recovery. To estimate the fractions of biomass converted to various HWP, pulp chips, and residue from 1950 to 2000, we further assumed a linear transition from the fractions estimated for 1940 to those estimated for the period 1999 to 2010[2]. The conversion from industrial roundwood to solid HWP and the disposal of mill residue for the study period, from 1901 to 2010, are summarized in Table S3.

For pulp and paper manufacturing, hog fuel produced from debarking and chipping processes and black liquor produced from pulping were estimated following Chen et al.[2]. Based on reported North American pulp production for 1919 to 1940[10], we estimated that for 1900 to 1950, mechanical and chemical pulp accounted for 47.7 and 52.3% of total pulp production in Canada, respectively.

Table S3. Fractional shares of harvested biomass carbon among solid harvested wood product types and the different uses and disposal options for sawmill residue immediately after product manufacturing

Period	Lumber	Structural[§]	Nonstruct[¶]	Pulp chip	Energy	Landfill	Stockpile	Emission[†]
1901-1940	0.375	0.050	0.000	0.000	0.000	0.287	0.144	0.144
1941-1950	0.375	0.050	0.010	0.052	0.019	0.241	0.120	0.132
1951-1960	0.375	0.050	0.021	0.103	0.039	0.195	0.097	0.120
1961-1970	0.375	0.050	0.031	0.155	0.058	0.149	0.073	0.109
1971-1980	0.375	0.050	0.042	0.206	0.078	0.102	0.049	0.098
1981-1990	0.375	0.050	0.052	0.258	0.097	0.056	0.025	0.087
1991-2000[‡]	0.375	0.050	0.063	0.309	0.116	0.010	0.002	0.075
2001-2010[‡]	0.375	0.050	0.063	0.309	0.116	0.010	0.002	0.075

[§] Structural panel products, including plywood and oriented strand board.

[¶] Non-structural panel products, including particleboard, medium density fibreboard, hardboard, and insulating board.

[†] Emission includes wood carbon emitted from biomass combustion without energy recovery and from biomass decomposition.

[‡] Fractions for 2001 to 2010 were from Chen et al.[2] while those for 1900 to 1990 were estimated as described above.

Production and use of wood bioenergy by the Canadian HWP sector was low prior to 1960 but subsequently increased rapidly[9]. Before 1970, U.S. sawmills used mostly fossil fuel to meet their energy needs, and while U.S. pulp mills also relied heavily on fossil fuels, burning wood residue and black liquor provided about 38% of their energy[11]. In recent years, the U.S. HWP industries have used most of their mill residue to produce energy[12]. We assumed all of Canada's HWP industries had similar wood energy use before 1970.

Based on the above information, we assumed that prior to 1950, 45, 40, and 15% of mill residue was landfilled, burned as waste, and left in stockpiles, respectively. We also assumed that for the period 1901 to 1950, on average, 30% of black liquor produced by Canadian pulp mills was used to produce energy and 70% was disposed of in industrial landfills, compared to 95% burned to produce energy and 5% landfilled for 2004 to 2010[2]. We calculated mill residue disposal fractions for 1950 to 2000 by assuming a linear transition from values estimated for 1900 to 1950 to those for 2004 to 2010[2].

Production Emissions of Canadian Harvested Wood Products. We calculated emissions caused by producing major types of solid HWP in Canada based on cradle-to-gate emission assessments by the Athena Sustainable Materials Institute (ASMI)[13-17]. We similarly derived production emission factors for Canadian-made lumber, OSB (oriented strand board), particleboard, and MDF (medium density fibreboard) using data from the Forest Products Association of Canada (FPAC)[18]. The emission factor for lumber production derived from FPAC values[18] was twice that reported by ASMI[15], whereas the production emission factors for OSB, particleboard, and MDF derived from FPAC values[18] were smaller than those derived from the ASMI study results[14,16,17]. To avoid underestimating production emissions, we used the larger of the two emission factors, i.e., the emission factor for lumber production from FPAC[18] and the emission factors for other solid HWP derived from ASMI (Table S4).

Table S4. Production emission factors for Canadian-made harvested wood products (HWP) (kg CO_2eq per tonne of carbon in HWP)

Product type	Emission factor[¶]	Data source
Solid harvested wood products[§]	411.5	
Lumber	297.4	FPAC 2011[18]
Structural panels[§]	870.0	
Plywood[†]	877.7	Athena Sustainable Material Institute[13]
OSB[†]	866.6	Athena Sustainable Material Institute[14]
Non-structural panels[§]	725.2	
Particleboard[†]	646.8	Athena Sustainable Material Institute[16]
MDF[†]	1,165.0	Athena Sustainable Material Institute[17]
Pulp, paper and paper products[§]	1,173.7	
Chemical pulp	578.1	Summarized from Canadian data provided by Jon
Mechanical pulp	1,098.4	McKechnie, Faculty of Engineering, University of
Paper and paper products	1,628.1	Nottingham (pers. comm., 2013).

[¶] Emission factors were defined as greenhouse gas emission (kg CO_2eq) from fossil fuel combustion from producing a tonne of carbon in HWP, including fossil fuel use in forest harvesting, wood transportation, HWP manufacturing, as well as indirect emissions from fossil fuel use for purchased electricity.

[§] Emission factors were weighted averages based on HWP fractions estimated for Canadian HWP sector[2].

[†] Emission factors for solid HWP were converted from values estimated in the specific references in different units: conversion to m^3 from various solid HWP measurement units used in the references, e.g., Mfbm (1,000 board feet) for lumber, MSF (1,000 square feet on 3/8” basis) for plywood, and HWP carbon content (kg carbon per m^3 HWP) based on Meil et al.[5].

We found no published data for product-specific emission factors for Canadian pulp and paper products. Thus, we relied on non-published Canadian data (Jon McKechnie, Faculty of Engineering, University of Nottingham, pers. comm., 2013) for these production emission factors (Table S4). The average emission factor for all Canadian-made pulp, paper, and paper products was estimated as 1,189 kg CO_2eq per tonne carbon, slightly larger than the factor estimated for pulp and paper products produced in Quebec for 1990 to 2006[19], which was 1,140 kg CO_2eq per tonne carbon in products.

END USES OF SOLID HARVESTED WOOD PRODUCTS PRODUCED IN CANADA

Based on Cohen[20], we estimated that 42.9, 21.4, and 35.7% of total lumber in North America in 1976 was consumed by residential construction, residential repair and remodelling, and other uses, respectively. The 42.9% of lumber consumed by residential construction in 1976 was divided proportionally into 37.6 and 5.3% for single- and multi-family house construction, respectively, based on the estimated fractions of these two end-use categories for 2004 to 2010[2], in which 24.3, 3.4, 26.7, and 45.6% of Canadian-made solid HWP were estimated to be consumed by single-family house construction, multi-family house construction, residential repair and remodelling, and other uses, respectively. We then used linear interpolation to approximate the end use fractions for the end of each decade from 1950 to 2010 (Table S5).

For structural and non-structural wood panels, end use fractions were estimated using data from the United States for 1948, 1962, 1986, and 1998[21]. Since the United States has been the largest consumer of Canada's HWP, and because there is a lack of Canadian HWP end-use data, these U.S. end-use fractions were applied to Canadian wood-based panel products. We calculated the end-use fractions for the end of each decade from 1950 to 2010 for Canadian HWP using linear interpolation (Table S5).

Table S5. End use matrix of Canadian-made solid harvested wood products by decade for 1950 to 2010 (based on previous studies[2,20,21])

Product type and end use	1950	1960	1970	1980	1990	2000	2010
Lumber							
Single-family house	0.500	0.453	0.405	0.357	0.310	0.262	0.243
Multi-family house	0.070	0.063	0.057	0.050	0.043	0.037	0.034
Residential repair and remodel	0.165	0.184	0.203	0.222	0.241	0.259	0.267
Other uses[§]	0.265	0.300	0.336	0.371	0.407	0.442	0.456
Structural panels							
Single-family house	0.357	0.310	0.349	0.409	0.453	0.427	0.342
Multi-family house	0.106	0.093	0.073	0.053	0.040	0.041	0.044
Residential repair and remodel	0.152	0.167	0.189	0.213	0.222	0.228	0.263
Other uses	0.385	0.430	0.389	0.326	0.285	0.304	0.351
Non-structural panels							
Single-family house	0.236	0.221	0.196	0.168	0.147	0.149	0.167
Multi-family house	0.079	0.071	0.053	0.033	0.020	0.021	0.022
Residential repair and remodel	0.127	0.161	0.192	0.224	0.202	0.133	0.159
Other uses	0.558	0.547	0.559	0.575	0.631	0.697	0.652

[§]Accounts for all uses of Canadian solid harvested wood products except that used in residential construction, e.g., in non-residential construction, manufacturing, shipping, and packaging.

ESTIMATING CARBON STOCKS OF PRODUCTS IN USE AND IN LANDFILLS

The forest carbon balance in the present study was estimated based on published literature. Here we focus on the methods used in HWP-CASE (a HWP model for Comprehensive Assessments of carbon Stocks and Emissions) to simulate the complicated dynamics of carbon stocks of HWP in use and post-disposal HWP and mill residue, the two most important components in the life-cycle analysis of HWP carbon balance[2,21],for HWP produced in Canada between 1951 and 2010.

Estimating Carbon Stocks of HWP in Use. The in-use HWP carbon stock was estimated by end use category using Equation S1, a modification of the first-order decay model[22]:

$$C(t+1) = C(t) \times e^{-10k} + C_i(t+1) \times e^{-5k} \tag{S1}$$

where: t is the decade ($t=0, 1, 2, ...$), in which $t=0$ represents all years prior to 1901, and $t=1$ the first decade (1901-1910), and so on; $C(t)$ is the carbon stock of the HWP in use at the end of decade t. The product of $C(t)$ and the exponential function describes carbon in HWP retained in use from decade t to decade $t+1$; k is the constant annual rate at which HWP placed in an end use goes out of use, estimated as $k = \ln(2)/t_{1/2}$, where $t_{1/2}$ is the half-life of the HWP in the end-use (described later); $C_i(t+1)$ is the inflow of the HWP carbon to the end use during decade $t+1$. Multiplying $C_i(t+1)$ and the exponential function yields the carbon in $C_i(t+1)$ retained in use at the end of decade $t+1$, assuming $C_i(t+1)$ enters the in-use category evenly over the decade, and thus on average, it has a decay time of 5 years. The half-lives of HWP used in this study were 85, 50, 25, 20 and 2.5 years for major end use of single-family house construction, multi-family house construction, residential repair and remodelling, other use of solid HWP, and pulp and paper products, respectively[21].

Estimating Carbon Stocks and Methane Emissions of Discarded HWP and Mill Residue. The carbon stock of retired HWP at the end of a decade was estimated as the sum of the HWP carbon stock of an end-use at the end of the previous decade and the inflow HWP carbon stock in the present decade, minus the HWP carbon stock at the end of the present decade. The retired HWP carbon was divided among different disposal pathways using fractions that varied from 1901 to 2010[2]. The disposal and carbon dynamics of discarded Canadian HWP and mill residue is illustrated in Figure S1.

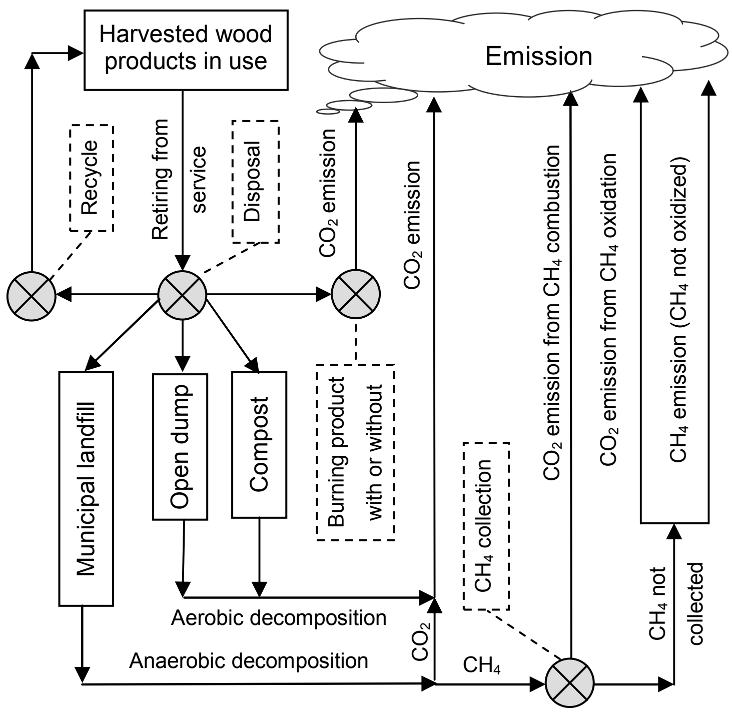

Figure S1. Carbon conversion from harvested wood products beyond the end of their service life. CO_2: carbon dioxide; CH_4: methane (Reprinted from Chen, J.; Colombo, S.J.; Ter-Mikaelian, M.T. *Carbon Stocks and Flows from Harvest to Disposal in Harvested Wood Products from Ontario and Canada*. Ont. Climate Change Res. Rep. CCRR-33; Ont. Min. Nat. Resour., Appl. Res. Develop. Br., Sault Ste. Marie, ON, Canada, 2013.[2] Copyright 2013 Ontario Ministry of Natural Resources and Forestry).

Equation S1 was also used to estimate the HWP carbon stock in dumps using half-lives of HWP in dumps[21]: 16.5 and 8.3 years for solid HWP and paper products, respectively.

For retired HWP and mill residue disposed of in landfills, the carbon stock consists of two components: the fraction of the HWP carbon that does not decompose, and the carbon retained in the degradable fraction of a HWP, estimated using equations S2 and S3, respectively:

$$C_p(t+1) = C_p(t) + C_i(t+1) \times (1 - D_f) \tag{S2}$$

$$C_d(t+1) = C_d(t) \times e^{-10k} + C_i(t+1) \times D_f \times e^{-5k} \tag{S3}$$

where: t and k are defined as the same as for Equation S1, and $t_{1/2}$ is the half-life of a solid HWP or paper and paper product in landfills[21]; $C_p(t)$ the fraction of landfill HWP carbon that does not decompose and $C_d(t)$ the retained carbon of the fraction that decomposes, at the end of decade t; $C_i(t+1)$ the carbon of HWP disposed of in landfills during decade $t+1$; D_f the fraction of HWP carbon disposed of in landfills that ultimately decomposes[21]; and, $C_p(0)$ and $C_d(0)$ are the carbon stocks of the non-degradable and degradable portions of HWP in landfills at the end of 1900. We assumed $C_p(0)=0$ and $C_d(0)=0$ because these values were expected to be quite small relative to more recent decades.

Assuming anaerobic decomposition of HWP in landfills converts the decomposed carbon equally into methane and carbon dioxide[22], landfill methane generation was estimated using Equation S4:

$$M_{gen}(t+1) = 0.5 \times (C_d(t) \times (1 - e^{-10k}) + C_i(t+1) \times D_f \times (1 - e^{-5k})) \tag{S4}$$

where: $M_{gen}(t+1)$ is methane generated in decade $t+1$; all other parameters and variables were defined as for equations S1 to S3.

We accounted for the collection and combustion of landfill methane that was converted to carbon dioxide, either with or without energy recovery. We used rates of landfill methane collection and combustion for energy recovery estimated for Canada[23] and the United States[24] to calculate weighted-average rates for all landfilled HWP produced by Canada.

In addition, it is estimated that 36% of the landfill methane that reaches the top layer of waste covering soil in a landfill is oxidized to carbon dioxide by bacteria in the soil[25]. Thus, the estimated landfill methane emissions accounted for not only methane generation and collection, but also oxidation, as described in Equation S5:

$$M_{emit}(t+1) = M_{gen}(t+1) \times (1 - R_{col}) \times (1 - R_{oxi}) \quad \text{(S5)}$$

where: $M_{emit}(t+1)$ is the potential landfill HWP methane emission in decade $t+1$, R_{col} landfill methane collection rate, and R_{oxi} the oxidation rate for methane reaching the top layer of waste covering soil.

ESTIMATING WOOD PRODUCT CARBON BALANCE, 1901-1950

The carbon stocks of in-use Canadian-made HWP by the end of each decade for the period 1901 to 1950 were estimated and used to determine the decadal production of HWP, emission from HWP manufacturing, and production and disposal of mill residue. Finally, the end use and end-of-life disposal of the HWP were analyzed to produce the carbon balance for HWP produced in Canada between 1901 and 1950.

Production of Harvested Wood Products. Carbon stocks of in-use Canadian HWP for 1930, 1940, and 1950 were obtained from a previous study[9]. To estimate the carbon stocks of HWP in use for 1910 and 1920, we applied a near zero carbon stock for 1900, and assumed a linear increase from 1900 to 1930. Using the carbon stock of HWP in use at the end of each decade from 1901 to 1950, we estimated the decadal production of Canadian HWP using Equation S6:

$$C_i(t+1) = \frac{1}{e^{-5k}} \times (C(t+1) - C(t) \times e^{-10k}) \qquad \text{(S6)}$$

Equation S6 is a reformulation of Equation S1 with the parameters and variables defined as for Equation S1. Solid HWP produced in Canada prior to 1950 were assumed to be lumber and structural panels only, because the major non-structural panel products were not produced in significant quantities before then[8].

Production, Use, and Disposal of Mill Residue. Mill residue generated from producing lumber and structural panel products from 1901 to 1950 was estimated based on biomass conversion efficiencies for HWP[2,5]. Because the use of mill residue in manufacturing wood-based panel products[8] and producing energy and pulp chips was limited prior to 1950[9], we treated mill residue produced before then as pure waste. Due to the lack of data, we assumed 45% of mill residue was landfilled, 40% was burned as waste, and 15% remained in stockpiles.

For pulp and paper manufacturing, hog fuel produced from debarking and chipping processes and black liquor obtained as a by-product of pulping were estimated following Chen et al.[2]. Based on reported North America pulp production for 1919 to 1940[10], we estimated that from 1901 to 1950, mechanical and chemical pulp accounted for 47.7 and

52.3% of total pulp production, respectively. Until the early 1970s, sawmills in the United States used fossil fuel to meet their primary energy needs while burning wood residue and black liquor accounted for 38% of U.S. pulp mills' energy[11]. Similarly, the generation and use of wood bioenergy by Canadian HWP industries was minimal before 1960, after which it increased rapidly[9]. Similar to lumber mill residue disposal, for the period 1901 to 1950 we assumed pulp mill hog fuel disposal was 45% landfilled, 40% burned as waste, and 15% left in stockpiles. We also assumed that, prior to 1950, 30% of black liquor produced by Canadian pulp mills was used to produce energy and 70% was disposed of in industrial landfills.

End-of-Life Analysis for Harvested Wood Products. Carbon in retired Canadian HWP was assigned to one of three disposal pathways[2]: burned (without energy recovery), landfilled (starting in 1940), or disposed of in open dumps (the dominant waste disposal option prior to 1970 in North America[2]). The carbon stock of retired HWP by disposal pathway at the end of each decade from 1901 to 1950 was estimated following the method described before in this document.

Carbon Balance of Harvested Wood Products, 1901-1950. The carbon balance of HWP produced in Canada during the period 1901 to 1950 was estimated to be a net removal of 192 teragrams of carbon (TgC) from the atmosphere (Figure 3 in the main article), calculated as the cumulative results of increased carbon stocks of in-use HWP (97 TgC), mill residue and retired HWP in landfills and dumps (149 TgC); HWP production emission (29 TgC); and landfill CH_4 emission (25 TgC). The decadal change in carbon balance of HWP was always positive, rising from 26 TgC for 1901 to 1910 to peak at 272 TgC for 1981 to 1990, and then decreasing to 256 and 201 TgC for 1991 to 2000 and 2001 to 2010, respectively.

EMISSION REDUCTION FROM WOOD SUBSTITUTION

Emission Reduction from Using Wood Energy. On-site fossil fuel combustion, as well as the purchased electricity consumed by Canadian HWP industries, is associated with fossil fuel-based greenhouse (GHG) emissions. When a portion of the industry's energy consumption is supplied by mill residue-based energy, some fossil fuel emission is reduced. Because the emissions associated with mill residue (e.g., wood harvesting, transportation) are accounted for in HWP carbon balance analysis, the weighted-average emission (kg CO_2eq) associated with 1 GJ (gigajoule) energy from on-site fossil fuel combustion and purchased electricity is defined as the emission reduction factor for mill residue-based energy. This emission reduction factor can be converted to kg CO_2eq emission reduction per tonne of wood carbon by considering wood energy content and wood energy conversion efficiency.

The emission of on-site fossil fuel combustion (kg CO_2eq per GJ energy produced) from 1990 to 2010 was calculated using Canadian HWP industry's fossil fuel energy consumption and associated emissions[26,27], averaging 59.8 kg CO_2eq GJ^{-1}. Because upstream life cycle emissions for natural gas and fuel oil were estimated to be 13.2 and 14.1 kg CO_2eq GJ^{-1}, respectively (obtained from Natural Resources Canada's GHGenius 4.02a model, which is available from http://oee.nrcan.gc.ca/transportation/tools/17180; accessed January 15, 2014), the life-cycle emission factor for on-site fossil fuel combustion was estimated to be 73.3 kg CO_2eq GJ^{-1}. In comparison, the emission factor for electricity generated in Canada[26] was 63.2 kg CO_2eq GJ^{-1}.

A recent study[28] estimated that purchased electricity and wood-derived energy consumed by the Canadian HWP industry increased from 21.0% and 42.4% in 1990 to 25.6% and 54.4% in 2010, respectively, with energy produced from on-site fossil fuel combustion decreasing from 36.4% in 1990 to 18.8% in 2011. For Canadian pulp and paper industries, the use of fossil fuel energy increased from 1920 until about 1970, after which fossil fuel energy use declined sharply, accompanied by increased consumption of biomass-derived energy and slightly decreased use of purchased electricity[9]. We included the emission reductions from using mill residue-based energy to substitute for fossil fuels and purchased electricity in the calculation of HWP production emissions in Canada. Therefore, the substitution effects estimated for wood bioenergy are a part of the HWP carbon balance (Figure 3 in the main article), and should not be interpreted as additional mitigation contributions.

To calculate the reduced emission from using wood energy, we assumed that wood energy proportionally replaced on-site fossil fuel use and purchased electricity. An emission reduction factor of 67.9 kg CO_2eq GJ^{-1} wood energy was used as the weighted-average of the emission factors of on-site fossil fuel energy and purchased electricity, based on their fractions in the energy use mix of Canadian HWP industries[28]. Because wood has an energy content of 19.4 GJ per oven-dry tonne (ODT) of wood, and wood energy conversion efficiency was 75% (obtained from GHGenius 4.02a model), each ODT of wood can produce 14.6 GJ energy, providing an emission reduction of 988 kg CO_2eq from replacing on-site fossil fuel combustion and purchased electricity. Assuming carbon is 50% of wood dry mass, the emission reduction factor of wood-based energy is calculated as 1,976 kg CO_2eq (or 539 kg carbon) per tonne carbon in wood. This is slightly higher than the lower boundary of wood energy emission reduction of 0.5 to 1.0 tonne carbon of reduced emission per tonne carbon in wood biomass used in generating energy summarized by Sathre and O'Connor[4].

Landfill methane (CH_4) has an energy content of 50.4 GJ per tonne of gas[22]. The energy conversion efficiency for landfill CH_4 was estimated to be 0.80, calculated as the average of those for biomass (0.75) and natural gas (0.85) obtained from GHGenius 4.02a. Thus, burning a tonne of landfill CH_4 (i.e. 875 kg C) produces 40.32 GJ of energy. Assuming landfill CH_4 is used to produce electricity, we calculated an emission reduction factor of 2.5 tonne CO_2eq per tonne of CH_4, or 3.4 tonne CO_2eq (or 0.9 tonne carbon) per tonne carbon in CH_4.

Emission Reduction from Using HWP in Residential Construction. Sathre and O'Connor[4] produced an emission reduction factor of 2.1 tonne carbon per tonne carbon in HWP used to replace other materials, based on 21 studies that included various HWP end uses and post-service disposal alternatives. For the substitution analysis in the present study, we analyzed 7 studies selected among the 21 studies that analyzed HWP use in residential construction where carbon dynamics in forests was also considered, and produced an emission reduction factor of 2.4 tonne carbon of reduced emissions per tonne carbon in HWP used in residential construction (Table S6).

Among studies in Table S6, great diversity existed in assumptions, time frames, and carbon and emission components[4]. For example, some of the studies included the use of mill residue, slash, or retired HWP in producing energy and/or landfill HWP carbon stocks, and CH_4 emissions and collection for energy recovery. Where energy generated using slash and retired HWP is included in calculating emission reductions, it would provide a higher substitution benefit. Energy produced using these biomass sources is not included in HWP-CASE, but mill residue and landfill CH_4 burned to generate energy, as well as landfilled HWP carbon stocks are simulated in HWP-CASE. Thus, there would be some degree of double counting of these effects in our study, as analyzed below.

Table S6. Emission reduction factor for harvested wood products (HWP) used in residential construction (tonne carbon emission reduction per tonne carbon in HWP). The references cited here were selected among studies examined by Sathre and O'Connor[4] where HWP were used in residential construction and forest carbon dynamics was included.

Reference	End use	Emission reduction
Börjesson and Gustavsson[29]	Apartment	4.3
Eriksson et al.[30]	Apartment	6
Gustavsson et al.[31]	Apartment (Sweden)	3.7
	Apartment (Finland)	1.8
Petersen and Solberg[32]	Roof: wood vs. steel	0.5
Petersen and Solberg[33]	Roof: wood vs. steel	0.5
Petersen and Solberg[34]	Roof: wood vs. steel	0.5
Upton et al.[35]	Single-family house	3.7
	Single-family house	1.8
Average		2.4

The effects of double-counting CH_4-based energy on the total mitigation benefits were likely minor, because the emission reduction from using landfill CH_4 to generate energy in 1951-2010 (4 TgC) was small relatively to other emission reduction estimates in this study (see the Results section in the main article). In addition, of the 4 TgC emission reduction attributable to energy generation from landfill CH_4, only a small fraction would be attributed to HWP retired from residential construction, due to the long HWP service life in this end use and the low CH_4 generation rate of solid HWP in landfills[21].

The effects of double-counting mill residue in energy production can be analyzed by proportionally dividing mill residue used in energy generation among solid HWP and their end uses, following Chen et al.[2]. This way, we estimated that each tonne of carbon in Canadian-made HWP used in residential construction is associated with 0.2 tonne carbon of mill residue burned to generate energy, producing an emission reduction of 0.1 tonne carbon (calculated using the emission reduction factor for mill residue-based energy). In other words, the overestimated emission reduction for each tonne carbon in HWP used in residential construction from double-counting mill residue use in generating energy is roughly 0.1 tonne carbon.

SUMMARY OF HWP PRODUCTION, MILL RESIDUE PRODUCTION AND USE, AND HWP PRODUCTION EMISSIONS, 1901-2010

Harvesting removed 2,836 TgC from Canada's forests between 1901 and 2010, of which 34 and 21% was converted to solid HWP and pulp and paper products, respectively, 18% was burned to generate energy, and 26% was discarded as waste (Table S7). Harvesting was historically much less than it is now, with carbon removed from Canadian forests in the annual timber harvested from 2001 to 2010 almost 14 times more than that in annual timber harvesting a century earlier. In addition, the wood use efficiency of Canada's HWP industries has improved significantly, increasing from converting 46% of harvested wood to HWP from 1901 to 1910, with the remainder going to waste, to 65% utilization in products for 2001 to 2010 and 26% burned for energy (Table S7). Emissions from manufacturing HWP accumulated to an equivalent of 300 TgC, of which 106 and 194 TgC were from manufacturing solid HWP and pulp and paper products, respectively.

Table S7. Cumulative distribution of harvested wood among harvested wood products and residue disposals, and production emissions for Canada for the period 1901 to 2010 (teragrams of carbon)

Decade from 1901 to 2010	1	2	3	4	5	6	7	8	9	10	11	Total
Industrial roundwood input[§]	38.0	42.3	46.7	84.1	137.7	192.2	314.5	420.1	496.3	546.7	517.8	2,836.4
Solid wood products	11.1	12.8	14.5	25.9	42.9	44.8	87.6	133.7	172.5	215.1	214.7	975.6
Pulp and paper	6.5	6.7	7.0	12.8	20.4	46.4	69.5	89.1	107.9	117.5	120.8	604.6
Residue disposal in landfill	10.2	11.4	12.6	22.7	37.2	35.3	50.6	55.1	46.1	29.6	8.0	318.8
Residue disposal in stockpile	4.0	4.6	5.1	9.2	15.2	16.1	23.6	25.8	21.6	13.2	0.9	139.3
Residue burned as waste	6.2	6.8	7.5	13.5	22.0	24.3	35.4	42.1	43.8	43.1	34.6	279.3
Residue burned for energy						25.2	47.9	74.2	104.3	128.3	138.9	518.8
Production emissions	3.3	3.5	3.8	7	11.3	19.5	31.4	42.7	53.3	61.3	62.8	299.9
Solid wood products	1.2	1.4	1.6	2.9	4.8	4.6	9.1	14.2	18.7	23.7	24.1	106.3
Pulp and paper	2.1	2.1	2.2	4.1	6.5	14.9	22.3	28.5	34.6	37.6	38.7	193.6

[§] The carbon in industrial roundwood consumed by Canadian wood product industries in each decade (e.g., 1901-1910, 1911-1920), followed by the carbon distribution among product types and residue disposal pathways.

UNCERTAINTY ANALYSIS FOR THE CARBON BALANCE OF CANADA'S HARVESTED WOOD PRODUCTS, 1951-2010

Sensitivity Analysis. We developed *HWP-CASE* (a *HWP* model for ***C***omprehensive ***A***ssessments of carbon ***S***tocks and ***E***missions) to simulate the life-cycle carbon stocks and emissions for HWP produced in Canada between 1951 and 2010. HWP-CASE uses several modelling parameters and variables to simulate the complex HWP life cycle. We conducted a sensitivity analysis to determine the most sensitive parameters and variables; this provided an indication of the importance of the parameter and/or the carbon component associated with the parameter in terms of influencing the carbon sinks and sources of Canada's managed forest sector and wood substitution over the study period. Instead of separately evaluating HWP carbon balance and wood substitution effects as in the main article, they were combined as total GHG mitigation potential to produce a single set of sensitive parameters/variables. A pre-assessment was made to select parameters to which the mitigation potential from Canada's managed forest sector was potentially most sensitive (Table S8), and these were categorized into groups relevant to (a) wood carbon conversion during HWP manufacturing, (b) HWP carbon dynamics in their end uses, and (c) post-service HWP carbon stocks and emissions. Because of the high volume of lumber produced relative to other products, the sensitivity analysis was focused on lumber-related parameters. Harvest volume, the input for HWP-CASE, directly affects all aspects of the carbon balance of Canada's HWP, and thus was included in the sensitivity analysis. Lack of life-cycle information for HWP produced prior to 1951 resulted in high uncertainty associated with the initial HWP carbon stocks and emissions in 1950. These were treated as input variables and also tested in the sensitivity analysis (Table S8). Input variables (or those of the parameters) were increased by 10% of the value used in the present study one at a time, and the resulting percentage change in HWP life-cycle carbon balance and avoided fossil fuel emission from wood substitution, and the overall mitigation potential were compared to values presented in Figure 3 and Table 2 of the main article to calculate sensitivity to the tested variable or parameter.

As highlighted in Table S8, ten parameters, as well as harvest volume, were associated with a minimum 0.9% change in the total GHG mitigation potential. Carbon balance was most sensitive to harvest volume, log fraction, fraction of solid HWP used in residential construction, and pulpwood fraction. Notably, the analysis revealed that initial carbon stocks/emissions in 1950 estimated for Canadian HWP produced during the period 1901 to 1950 had little effect on the carbon balance for the entire study period of 1901 to 2010. This corresponds with the conclusions of a previous study of HWP produced in Ontario, Canada[36]. This reflects two factors: the stock of carbon in wood remaining in use or in landfill from forests harvested prior to 1950 was relatively stable and comparatively small relative to that of forests harvested post-1950.

Uncertainty Analysis. To provide upper and lower boundaries for an uncertainty analysis of the carbon balance of Canada's HWP and wood substitution contribution in reducing fossil fuel-based emission for the period 1951 to 2010, we used values reported in the literature to summarize the uncertainty of the most influential parameters, as well as harvest volume, to which HWP carbon balance is deemed sensitive (Table S9). Since log fraction and pulpwood fraction are inversely related (when one increases, the other

Table S8. Model sensitivity: the percentage change in carbon stocks/emissions, substitution effects, and total greenhouse gas (GHG) mitigation potential that results from increasing a single parameter or input variable by 10% of the value used in this study

Input variables and model parameters		**Change in carbon stocks**			**Change in GHG emissions**			**Change in substitution effects**[€]		**Change in GHG mitigation potential**
		Industrial landfill	Municipal landfill	HWP in use	Production emissions[#]	Industrial landfill CH_4[¥]	Municipal landfill CH_4	HWP used in construction	Wood energy	
Input variables	Harvest volume[†]	8.5	9.5	9.5	9.0	7.0	9.7	10.0	10.0	**9.9**
	Initial conditions for 1950[±]	1.5	0.5	0.5	0.0	3.0	0.3	0.0	0.0	0.3
Parameters – carbon conversion during HWP manufacturing	Pulpwood fraction[‡]	-2.6	-0.2	-1.8	6.2	-2.5	3.4	-3.3	3.1	**-2.5**
	Log fraction[‡]	6.2	-0.3	5.7	0.4	5.0	-9.0	10.0	-9.7	**7.2**
	Lumber fraction in solid HWP[§]	0.0	-0.2	0.2	-3.2	0.0	-0.1	1.0	0.0	**1.0**
	Mechanical pulp chip fraction[¶]	4.1	1.1	0.4	1.5	2.7	2.0	0.0	-6.7	-0.5
	Chemical pulp chip fraction[¶]	5.5	-2.2	-0.9	-3.0	3.5	-4.1	0.0	0.4	**0.9**
	Production emission factor - Solid HWP	0.0	0.0	0.0	3.1	0.0	0.0	0.0	0.0	-0.5
	Production emission factor - Pulp and paper	0.0	0.0	0.0	5.9	0.0	0.0	0.0	0.0	-**0.9**
	Fraction of mill residue burned to produce energy	-5.1	0.0	0.0	0.0	-3.7	0.0	0.0	8.4	0.6

Parameters – HWP end-use carbon dynamics	Fractions of solid HWP used for residential construction	0.0	-1.9	1.5	0.0	0.0	-0.6	10.0	0.0	**4.3**
	Half-lives of all HWP in use	0.0	-4.7	4.3	0.0	0.0	-2.7	0.0	0.0	**0.9**
Parameters – post-disposal HWP carbon dynamics	Fraction of retired solid HWP disposed of in landfills	0.0	5.6	-0.5	0.0	0.0	1.6	0.0	0.0	0.8
	Fraction of retired paper and paper products disposed of in landfills	0.0	3.8	-0.9	0.0	0.0	7.7	0.0	0.0	-0.4
	Degradable fraction of solid HWP in landfills	-0.8	-0.4	0.0	0.0	6.1	1.4	0.0	0.0	**-0.9**
	Degradable fraction of paper and paper products in landfills	0.0	-2.2	0.0	0.0	0.0	8.7	0.0	0.0	**-1.4**
	Half-life of solid HWP in landfills	0.7	0.3	0.0	0.0	-5.0	-1.2	0.0	0.0	0.8
	Half-life of paper in landfills	0.0	1.1	0.0	0.0	0.0	-4.4	0.0	0.0	0.7
	Landfill CH_4 collection rate	0.0	0.0	0.0	0.0	0.0	-2.1	0.0	0.0	0.2
	Landfill CH_4 oxidation rate	0.0	0.0	0.0	0.0	-4.8	-5.8	0.0	0.0	**1.1**

[¥] Methane.

[†] Volumes of both pulpwood and logs are increased by 10%.

[±] Carbon stocks of HWP in use and carbon in landfills for 1950 are both increased by 10%.

[‡] Pulpwood volume is increased by 10%, while log volume is decreased by the same amount. Similarly, when log volume is increased by 10%, pulpwood volume is reduced.

[§] Lumber fraction in logs increased by 10%; structural and non-structural panel decreased proportionally by a total of 10%.

[¶] Pulp chip consumption fraction increased by 10% for one pulp type, and reduced by same amount for another pulp type.

[#] Production emissions include emissions from 1901 to 1950 plus those estimated for 1951 to 2010; only the latter was affected by increased harvest volume.

[€] Substitution effects in reducing fossil fuel emissions were estimated for the period 1951 to 2010 in the present study.

decreases), the more sensitive parameter, log fraction (Table S8), was used in the analysis. A worst case scenario was simulated by combining the high- or low-boundary values for these parameters to minimize the overall mitigation potential during the period 1951 to 2010. Similarly, a best case scenario was simulated that maximized the mitigation potential. These scenarios provided the ranges of carbon balance values and wood substitution effects for Canadian-made HWP during the period 1951 to 2010 that are presented in the article.

Table S9. Uncertainty associated with volume of industrial roundwood harvested in Canada and the key parameters for estimating carbon balance for Canada's harvested wood products (HWP)

Parameter/variable	Uncertainty	Source
Harvest volume	±10%	
Log fraction	±10%	
Lumber fraction in solid HWP	±20%	Skog[21]
Pulp chip fraction - Chemical pulp	±20%	
Production emission factor - Pulp and paper	±15%	
Fractions of solid HWP used for residential construction	±20%	Dymond[37]
Half-lives of solid HWP in use	±50%	Skog[21], IPCC[22],
Half-lives of paper and paper products in use	±32%	Skog[21]
Degradable fraction of solid HWP in landfills	0.013 - 0.346[§]	Skog[21]
	±10%	IPCC[22]
Degradable fraction of paper and paper products in landfills	0.448 - 0.671[§]	Skog[21]
Landfill methane oxidation rate	±6%	Chanton et al. [38]

[§] Uncertainty in the degradable fraction was given as a range by Skog[21]; high and low boundary values were used in the uncertainty analysis.

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