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forest ecology

A Comprehensive Greenhouse Gas Balance for a Forest Company Operating in Northeast North America

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Greenhouse gas (GHG) emissions and carbon stock changes projected over 100 years were quantified for a company managing 2.2 Mha of forest in northeast North America. From 2010 to 2015, company forest operations, sawmills, and pulp/paper mills were forecast to contribute 21, 4, and 75%, respectively, of total emissions. Forest and products were forecast to result in an increasing cumulative net GHG (sequestration minus emissions) sink to 30.7 t CO_2e ha^{-1} at year 50, but as harvest levels increased, emissions exceeded sequestration by year 85, reaching a GHG source of 6.4 t CO_2e ha^{-1} by year 100. After 100 years, the ratio of forest product storage to all emission pools was 0.58, 0.84 if grid electricity was hydrogenerated, or 2.7 if pulpwood was redirected for bioenergy. Determining the GHG mitigation potential of forest products requires inclusion of wood, paper, bioenergy, and manufacturing emissions and consideration of natural disturbances, leakage, and avoided emissions.

Keywords: greenhouse gas, carbon, life cycle, forest management, pulp and paper, wood products, product substitution

Greenhouse gases (GHGs) emitted from human activities (e.g., deforestation and fossil fuel use) and natural forest disturbances (e.g., insects and fire) contribute to warming of the earth's climate. This warming could potentially have severe economic and social impacts around the globe. In 2005, forest products in the United States stored up to 44 Tg of carbon (C), equivalent to 25% of US net forest C sequestration that year. This C stored in forest products was equivalent to 61% of residential GHG emissions in the United States (Skog 2008).

The potential change in net GHG emissions due to altering C stored in both forests and forest products has been evaluated for varying silviculture treatments and harvest rates in northeastern North America (Hennigar et al. 2008). However, few studies have quantified the change in net GHG emissions from modifying activities associated with an entire integrated forest enterprise. Evaluation of the effects of altering forest product production should include substitution of nonrenewable materials (e.g., concrete and steel) for solid wood lumber products, which can cause on average 2.1 t C of additional emissions released per t C stored in solid wood product replaced (Sathre and O'Connor 2010). Previous studies have excluded pulp and paper manufacturing, a core component of economically viable lumber manufacturing in most regions. Studies differ in C storage pools considered; for example, only 8 of 49 studies accounted for C dynamics in the forest and only 3 accounted for C in wood products (Sathre and O'Connor 2010).

Studies of GHG emissions have been conducted for production of individual solidwood products (Bergman and Bowe 2008, Athena Institute 2009, Natural Resources Canada 2010), pulp and paper products (Françis et al. 2002, Worrell et al. 2008, Ecofys Group 2009), and emissions from associated forest operations (e.g., Johnson et al. 2005, Oneil et al. 2010, Carle et al. 2011). Results of such studies vary substantially, depending on facility type/configuration, machine productivity, and inventory accounting boundaries.

In this study, we first build a comprehensive GHG storage and emission profile for J.D. Irving, Limited (JDI), a vertically integrated forest company operating on 2.2

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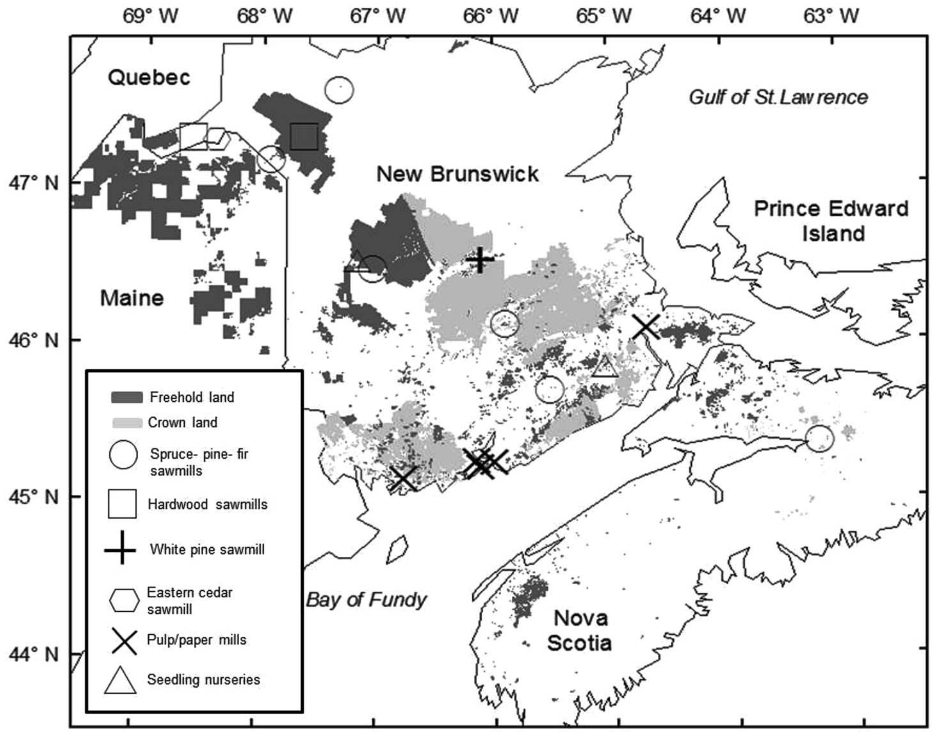

Figure 1. JDI forest management area (2.2 Mha) in Maine, New Brunswick, and Nova Scotia, and operating sawmills (10), pulp and paper mills (4), and tree nurseries (2) at the time of this study. Two additional tissue mills in Toronto and New York are not shown, but emissions were accounted for in the analysis.

Mha in northeast North America. GHG emissions included those associated with harvesting, transporting, and manufacturing solid wood and pulp products; grid electricity; fossil fuel production and transport; and third-party manufacturing of wood harvested on the study site. Second, we used these data to conduct a dynamic attributional life cycle assessment (LCA) by estimating cumulative net GHG emissions over 100 years for all JDI enterprises. This included C storage changes in forests and wood products, GHG emissions associated with manufacturing wood products, and CH_4 emissions in landfills over a 100-year period. Third, we estimated cumulative net emissions for cases that differ from the baseline case by assumed changes to (1) landfill CH_4 capture rates, (2) grid electricity production source, (3) pulpwood diversion to use for power production, and (4) a no management scenario in which lumber and pulp products are not produced, forests are not harvested, and nonrenewable products replace structural wood products. The no harvest scenario, although unrealistic because world wood fiber demands are expected to triple by year 2050 due to increases in societal demands (World Wildlife Federation 2013), is presented to aid discussion of natural disturbance, substitution, and leakage considerations in this analysis.

Methods

Attributional LCA Accounting Boundary Overview

JDI is an integrated forest products company that manages forest located throughout New Brunswick (NB) and Nova Scotia, Canada, and Maine, USA. The landbase includes 1.2 Mha owned by JDI and 1 Mha of licensed NB Crown (publicly owned) forest (Figure 1). JDI regularly performs a wide range of harvesting and regeneration interventions across their land; see Etheridge et al. (2005) for a more detailed description of forest management objectives and operations on JDI NB private land and Erdle and Ward (2008) for information on NB Crown land. At the time of this study in 2010–2011, JDI was operating 11 sawmills, 1 kraft pulp mill, 1 mechanical pulp and specialty paper mill, 1 semichemical pulp and corrugated paper mill, 3 tissue mills, and 2 tree nurseries (Figure 1).

Using the JDI current management strategy, we accounted for all C stock changes and GHG emissions projected to occur over 100 years from (1) forest (live and dead biomass) C stocks, (2) forest operations emissions, (3) wood product manufacturing and wood energy emissions, (4) C stocks in wood products in use and in landfills, and (5) landfill CH_4 emissions (Figure 2). Harvest and silviculture treatments varied over time in the baseline projection, but current management objectives, harvesting systems, mill and product manufacturing distributions, and GHG emission rates were held static over the projection period for this comparison.

Forest and Management Modeling

The JDI forest estate management model (built with the Remsoft Spatial Planning System; Remsoft, Inc. 2010), included all 2.2 Mha of productive forest and was used to project the baseline schedule of harvest and regeneration treatments in combination with forecasting forest development for 100 years in 5-year planning periods. Treatments were scheduled by JDI to maximize spruce-fir-jack pine (*Picea* spp.-*Abies balsamea* [L.] Mill.-*Pinus banksiana* Lamb. [SFJ]) and hardwood harvest over 100 years,

Management and Policy Implications

We analyzed greenhouse gas (GHG) emissions and carbon stock balance, including forest, products, forest operation emissions, purchased electricity emissions, and potential substitution benefits, for J.D. Irving, Limited, a vertically integrated forest products company that owns or manages 2.2 Mha of forest. Results demonstrated how the forest, wood products, and emissions avoided contribute to GHG balance and the significance of manufacturing emissions from wood product production. We provide a method that practitioners can use to evaluate how forest, harvest regimes, and product distributions influence GHG balance and synthesize parameters for use in estimation of emissions from different harvesting, transporting, and manufacturing systems. This analysis of all emission and storage GHG pools for a large Canada/United States landbase provides practitioners and policymakers with insight on how to focus efforts to improve GHG balance. Such analyses should include forest operations and manufacturing emissions and consider natural disturbances, leakage, and avoided emissions.

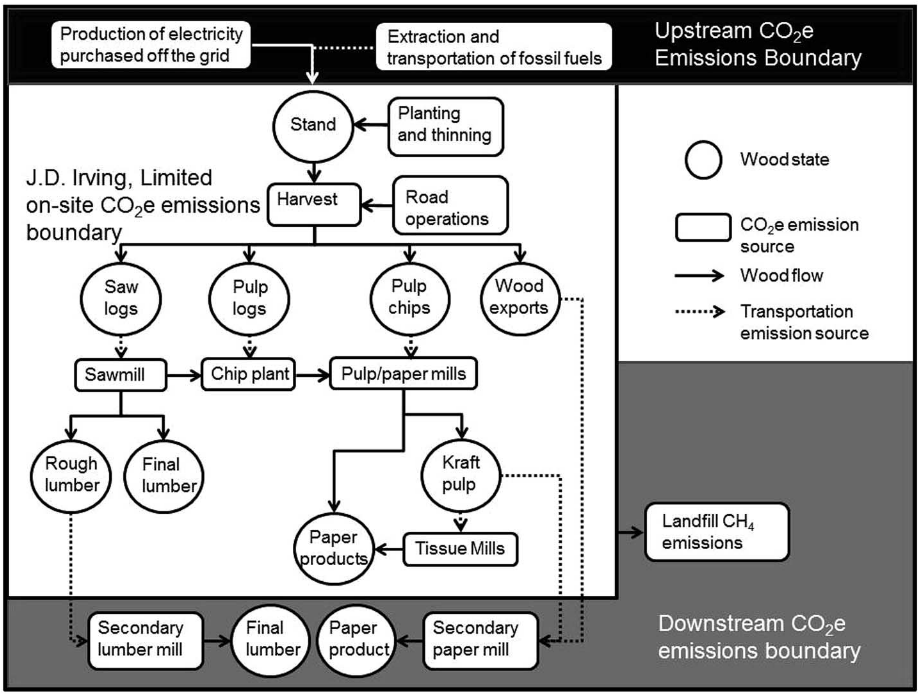

Figure 2. Emission accounting boundaries for upstream emissions (production and delivery of electricity and fossil fuels), on-site emissions (fossil fuels used by forest operations and mills), and downstream emissions (third-party manufacturing of log or wood product exports) resulting from production of forest products from JDI managed lands.

constrained by (1) nondeclining SFJ harvest, (2) nondeclining hardwood harvest after year 2025, (3) maximum and minimum periodic area planted by district, (4) nondeclining operable growing stock for the last 10 years of forecast, and (5) harvest restrictions for ecologically sensitive areas (e.g., wildlife habitat, water courses, and protected areas).

Stand development was forecast using a calibrated empirical stand table projection model. For this analysis, volume projections by sawlog and pulp products were aggregated into five species groups based on JDI mill feedstock constraints: SFJ, cedar (*Thuja occidentalis* L.), white pine (*Pinus strobus* L.), shade-intolerant hardwoods, and shade-tolerant hardwoods. Other softwood species (*Larix laricina* [Du Roi] K. Koch, *Pinus resinosa* Sol. ex Aiton, and *Tsuga canadensis* [L.] Carrière) were tracked individually within the model, however, because they comprised <2% of current merchantable volume, they were combined with SFJ.

The C Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) was used to translate each stand type merchantable volume projection into forecasts of C yield for live (above- and belowground) and dead (forest floor, standing deadwood, and downed deadwood) biomass pools. See Hennigar et al. (2008) for a more detailed description of this process and soil pool initialization assumptions and Kurz et al. (2009) for details on CBM-CFS3 assumptions and structure.

Forest Operations Emissions

JDI 2009–2010 diesel fuel consumption and productivity data were compiled by machine within four harvest systems: (1) feller buncher, skidder, shovel logger, and processor; (2) single-grip harvester and 14- or 18-t forwarder; (3) feller buncher, flail chipper, shovel logger, and four-wheel drive skidder; and (4) commercial thinning mid-sized wheeled harvester and forwarder. The proportion of volume harvested by each system varied among five management units and was fixed within the model according to unit usage in 2010. Diesel consumption for floating (transporting harvesting machines between harvest sites) was estimated (Dwayne Prest, JDI, pers. comm., June 1, 2010) and ranged from 0.3 to 0.55 L of diesel consumed per tonne of C in dry biomass of wood harvested. Mean diesel consumption coefficients for transportation of harvested wood (logs, chips, and hog fuel) from the harvest site were estimated using fuel burn rates (L km^{-1}) for five truck types (self-loader, b-train, chip-van, off-road self-loader, and off-road chip van), travel distances per mass of product, and percent mass transported by each truck type. Diesel consumption coefficients were also estimated and compiled for cumulative 2010 road construction, grading operations, and cross drain and brook-crossing installations. Levels of road construction (700 km $year^{-1}$) were projected to decrease by one-third every 5 years for the next 30 years and then remain constant as the landbase becomes fully accessible; however, road maintenance of core arteries was assumed to remain constant through the forecast (Dwayne Prest, JDI, pers. comm., June 1, 2010).

Forest-level diesel consumption from wood extraction (DWE) activities for each of the 20 5-year modeling periods p was expressed within the forest estate model as

$$DWE_{p=1}^{P=20} = \sum_{s=1}^{S=5}\sum_{d=1}^{D=5} c_{psd}h_{sd} + \sum_{d=1}^{D=5} c_{pd}(t+f)_d + \sum_{d=1}^{D=5} r_{pd} \quad (1)$$

where c is tonnes of C extracted by district d and harvest system s; h, t, and f are diesel consumption coefficients (liters per tonne of C) for harvest system, forest to mill transport, and harvest machine floating, respectively; and r is a time-dependent estimate of diesel consumed for all planned road operations.

Average grid electricity (0.06 kWh), diesel (0.003 L), and fertilizer inputs (0.4 g) per seedling output for the two JDI nurseries were estimated for 2010 (Hartmut Kunze and Nicolas Haché, JDI, pers. comm., Sept. 1, 2011). Each planted ha was assumed to require site scarification (35 L of diesel), 2,200 seedlings, transport of seedlings (2 L of diesel) and planters (16.3 L of gasoline), and follow-up aerial herbicide treatment (12.3 L of Jet A1) (Andrew Willett, JDI, pers. comm., Nov. 10, 2012). We assumed precommercial thinning operator productivity of 0.05 ha per productive machine hour and gasoline consumption of 1 L per productive machine hour (Holmsen 1988).

Appendix A summarizes CO_2e emission rate assumptions and data sources for production and on-site use per unit of electricity, fuel, and fertilizer consumed.

Manufacturing Emissions

Annual manufacturing inputs (wood, heavy oil, diesel, natural gas, propane, black liquor, and electricity) used in 2006 and 2007 for each sawmill facility and in 2009

Table 1. Forest harvest and trucking emissions from JDI operations (italic) compared with values from other studies.

Source	Emissions per m^3 processed by system[a]				
	Single-grip	Feller buncher	Flail chipper	Commercial thin	Trucking[b]
	(kg CO_2e m^{-3})				
This study: JDI	*11.29*	*15.24*	*17.47*	*9.48*	*6.44*[c]
Johnson et al. (2005)		8.51		7.50	15.78
Carle et al. (2011)	12.92	17.42	25.01		27.34
Oneil et al. (2010)		10.23			28.13
Natural Resources Canada (2010)	12.47				9.52
Mean literature value	12.70	12.05	25.01	7.50	20.19
JDI % of literature mean	89	126	70	126	32

[a] Calculated from reported diesel consumption and emission rates for stationary and mobile combustion conversion in Appendix A.
[b] Calculated for a 100-km one-way trip.
[c] Weighted average of all on- and off-road chip van, b-train trucks, and log truck activity across all JDI forest operations in 2010.

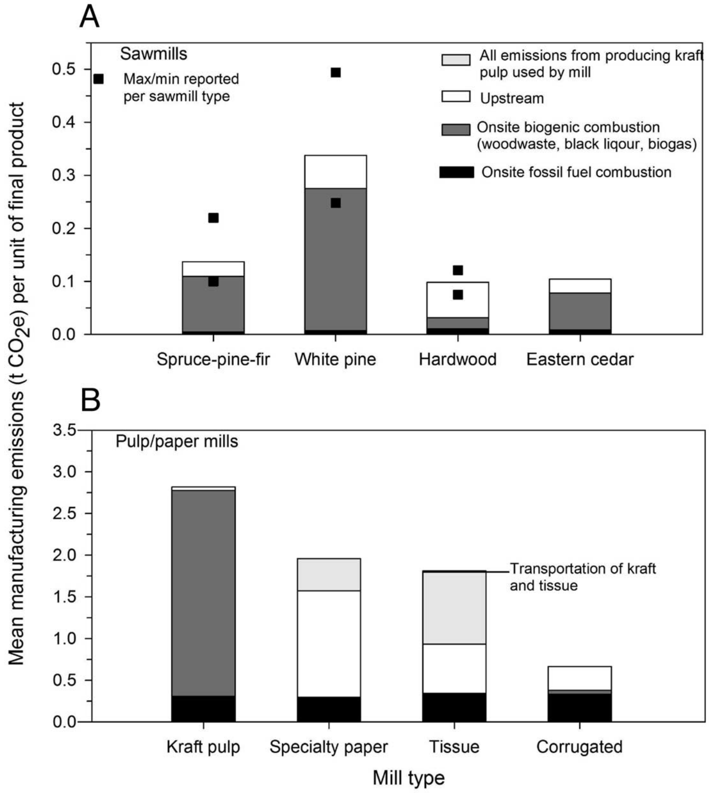

Figure 3. Proportion of mean CO_2e emissions from on-site fossil fuel, biogenic emissions (combustion of wood waste, black liquor, and biogas) and upstream (electricity and fossil fuel production/transport) sources per m^3 of solid wood product produced from four types of sawmills (A) and air dry tonne of product produced from four types of pulp and paper facilities (B) operated by JDI.

and 2010 for each pulp/paper facility, including mill yard activities, were compiled by JDI staff from annual purchase reports. The NB electricity production profile in 2008 comprised 58% nonrenewable fossil fuel sources and was held constant over the 100-year forecast[1] for this analysis. Upstream and on-site CO_2e produced from use of fossil fuels, biogenic fuel, and electricity were based on conversions in Appendix A and are expressed per unit of product by mill type (Figure 2).

Product shipments from the JDI 2009–2010 operating year were used to calibrate product flows into three main product pools: pulpwood and roadside chip exports, sawlog exports, and products requiring further processing (kraft pulp and rough lumber; Figure 2). Exported kraft pulp, pulp roundwood, and roadside chips were assumed to be converted to one-third each as specialty paper, newsprint, and cardboard, based on mean annual exports of paper products for Canada (Advameg, Inc. 2011); pulpwood and chip exports resulted in additional manufacturing emissions to account for conversion from raw material to kraft pulp (Appendix A).

Forest Product C Accounting

The Carbon Object Tracker (CO_T) model (Hennigar et al. 2008) was used to track C in wood removed from the forest by species-product group through conversion of raw wood to finished wood products, their in-life use, transfer to landfills, and decomposition. Integration of forest product C tracking into the forest management/wood supply model used methods similar to those of Hennigar et al. (2008). We calibrated the CO_T for JDI mills by performing a C mass balance of each mill's biomass inputs and outputs using 2010 consumption and utilization estimates and assumed that these transfer proportions would remain constant over the 100-year forecast.

Any harvested C not transferred to a final wood product pool was assumed to be immediately released to the atmosphere. CO_2 released from biomass use/disposal at mills was summarized by mill type but was not included in overall baseline results, as this would double the count against net stock changes reported in the forest pool. However, CH_4 and N_2O emissions from wood combustion, as well as CH_4 emissions from wood and paper decay at landfills, were included in baseline calculations; see Appendix B for conversion factors and references. The fate of C stored in final wood products and landfill decomposition were modeled on the basis of US harvested wood product accounting guidelines and related literature (Appendix B).

Net GHG Emissions over 100 Years under Alternate Scenarios

Net cumulative GHG emissions were estimated over 100 years for four alternate scenarios. First, the landfill CH_4 capture rate was assumed to increase from the average US value of 49% (US Environmental Protection Agency (EPA) 2002) to 90% after 30 years (EPA 2010), and captured CH_4 was assumed to displace grid electricity emissions, which were calculated as the difference between mean US grid (EPA 2010; because most JDI wood products are exported to the United States) and a landfill biogas-energy operation (Appendix B).[2] Second,

Table 2. Total estimated emissions from grid electricity generation and fossil fuel combustion per unit of production for facilities operated by JDI (italic) and comparison with literature values.

Mill type	Emissions per unit of production[a]			
		Literature values[b]		
	JDI	Average	Range	Reference
	(kg CO_2e)			
Sawmills				
Spruce-pine-fir	*32.50*	57.42	42.55–74.76	Bergman and Bowe (2010), Natural Resources Canada (2010), Athena Institute (2009)[c]
Hardwood	*77.28*[d]	101.90		Bergman and Bowe (2008)
White pine	*69.66*			
Cedar	*34.88*[d]			
Pulp and paper mills[e]				
Kraft pulp	*350.32*	473.04	238.75–740.08	Integrated Pollution Prevention and Control (IPPC) (2000), Françis et al. (2002), Worrell et al. (2008), Ecofys Group (2009)
Paper (via mechanical pulping)	*1,613.06*	1,830.72	1,625.94–2,005.68	Worrell et al. (2008), Ecofys Group (2009)[f]
Tissue	*913.72*[g]	613.01	322.73–802.59	IPPC (2000), Worrell et al. (2008)
Corrugated	*615.89*	514.25	223.72–859.03	IPPC (2000), Françis et al. (2002), Worrell et al. (2008)

[a] CO_2e emissions are per m^3 of kiln dry lumber for sawmills and per t of air dry product for pulp and paper mills.
[b] For comparison purposes, the cited mills were all assumed to use NB generation sources for electricity.
[c] Athena Institute (2009) excluded combustion of fossil fuels.
[d] Rough green lumber leaving the JDI mills was 95 and 54% of total lumber production for the hardwood and cedar mills, respectively.
[e] All non-JDI pulp/paper studies excluded combustion of fossil fuels used onsite for mill operations.
[f] Did not account for paper printing processes. An additional 618.54 t CO_2e per unit of production was added to account for these (Appendix A).
[g] Emissions from production and transportation of kraft pulp used by tissue mills were removed for comparison against other studies.

Table 3. Mean on-site fossil fuel combustion and upstream emissions per m^3 scheduled for harvest from 2010 to 2015 for JDI forest management area (2.2 Mha), assuming current silviculture regimes, trucking routes, road construction/maintenance levels, mill product distribution, and milling efficiencies.

Process	Emissions produced per m^3 harvested		
	On-site fossil fuel	Upstream[a]	% total on-site and upstream
	(kg CO_2e m^{-3})		
Planting + precommercial thinning	0.66	0.004	0.35
Road operations	1.67	0.005	0.89
Machine floating	3.39	0.057	1.83
Roundwood trucking[b]	14.76	0.24	7.96
Harvesting	19.42	0.29	10.45
Sawmill[c]	0.33	7.82	4.32
Pulp and paper mills[d]	45.48	94.41	74.20

[a] Upstream accounts for purchased electricity emissions and production and transportation of fossil fuels.
[b] Includes chip vans, self-loading trucks, b-trains, off-road chip vans, and off-road log trucks.
[c] Includes four mill types: SFJ, hardwood, white pine, and an eastern cedar mill.
[d] Includes four mill types: kraft pulp mill, tissue mills and converting facilities, corrugated paper product mill, and mechanical pulping special paper mill.

pulpwood was assumed to be redirected from pulp production for use in a gasifier for electricity generation, resulting in reduced NB grid source emissions (Appendix B). Third, electricity for manufacturing was assumed to change to alternative grid electricity sources (Appendix C). Fourth, we assumed no wood and pulp products being produced, no forest harvesting, and nonrenewable products replacing wood, resulting in increased manufacturing emissions by 2.1 t CO_2e per t CO_2e stored in solidwood products (average of 21 studies; Sathre and O'Connor 2010).

Results

GHG Emissions from Forest Operations and Wood Product Manufacturing

Our initial step analyzed emissions for all JDI operations and manufacturing. This showed that emissions per m^3 harvested for single-grip and feller buncher harvest systems were 6% lower and 26% higher, respectively, than the reported literature average values for the same systems (Table 1).[3] Commercial thinning operations were the least emission-intensive harvesting system (Table 1), mostly because a smaller, midsize harvester is used (Dave Maxwell, JDI, pers. comm., Sept. 10, 2010). The flail chipping system had 36, 13, and 46% higher emissions per unit volume compared with the single-grip, feller buncher, and commercial thinning systems, respectively (Table 1). Emissions from trucking operations were 68% lower than the average reported in other studies (Table 1), owing to use of off-road trucks with more than double the payload permitted on public highways and an efficient forest road network (straight and well-constructed), allowing increased and consistent travel speed.

Because of kiln drying requirements and relatively high emissions from wood waste combustion, JDI white pine sawmills produced 2.4–3.4 times more emissions per m^3 of output than other sawmill types (Figure 3A). At the time of this study, 95% of hardwood lumber and 54% of cedar solidwood products produced at JDI mills were not kiln dried or planed, which explains the lower emission rates compared with those for SFJ lumber (Figure 3A). The JDI SFJ lumber mills produced less GHG emissions per m^3 of production than hardwood, white pine, or cedar sawmills, resulting from 41% less grid electricity required per m^3 of production (Figure 3A). JDI SFJ and hardwood sawmills had 43 and 24% lower emissions per m^3 of lumber output than averages for similar mill types (Table 2). Softwood sawmills in Canada (Natural Resources Canada 2010) and the United States (Bergman and Bowe 2008, Athena Institute 2009) on aver-

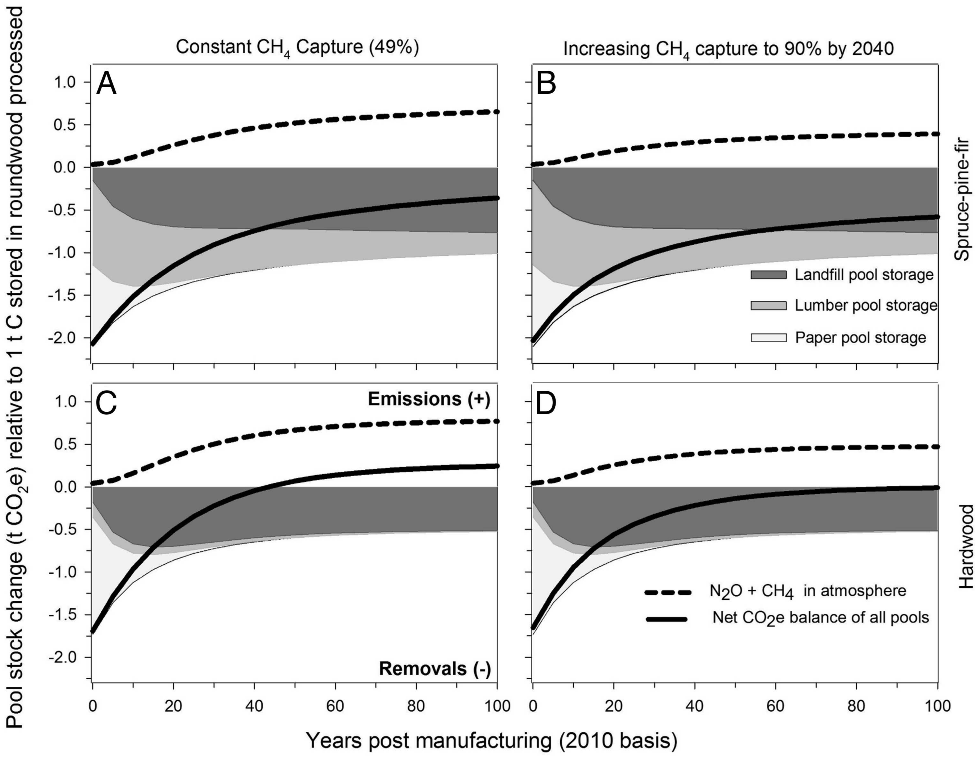

Figure 4. Forest product net emission balance over 100 years per unit of SFJ (A and B) and hardwood (C and D) merchantable tree bole (including bark) with constant CH_4 capture rate at 49% (A and C) and with CH_4 capture projected to increase to 90% by 2040 (B and D). Results are presented on a 2010 basis because of the time dependency of changes in CH_4 capture levels throughout the forecast. These include data on JDI current product distribution and mill utilization efficiencies, CO_2e retention in wood and paper products and landfills (Appendix B), and landfill CH_4 and N_2O emissions from product decomposition and combustion (Appendix B).

age required 34% more purchased electricity per m^3 of lumber than the average JDI sawmill (Table 2). JDI SFJ sawmills on average combusted 14% of sawlog fiber for on-site energy requirements versus 7% in Bergman and Bowe (2008). Three of seven SFJ sawmill sites also housed chip plants, where an additional 11% of pulpwood fiber was combusted for on-site energy requirements.

On-site fossil fuel and upstream emissions from the JDI kraft mill were 35% lower per tonne of pulp than reported literature values (Table 2), mostly as a result of recent biomass boiler installations. If, however, emissions from wood waste combustion were included, the kraft pulp mill emitted 31% more GHG per tonne than the mechanical pulp mill (Figure 3B). Primarily as a result of use of black liquor by-products for energy, the JDI pulp mill required little grid electricity (Table 2; Figure 3). Kraft pulp production for the JDI tissue mill accounted for 48% of tissue production emissions, with less than 1% coming from transportation of kraft pulp and unfinished tissue rolls (Figure 3B).

Estimated GHG Emissions and Fate of C Stored in Products Produced from 2010 to 2015

Our second step estimated the total emissions for JDI operations from forest to mill output gate for the period 2010–2015, C storage dynamics in products produced in that 5-year period over the next 100 years, and CH_4 emissions from those products in landfills. For this section, biogenic emissions and forest stock changes were excluded from accounting. Based on the JDI baseline management strategy, forest operations, sawmills, and pulp/paper mills were forecast to contribute 21, 4, and 75% of total upstream and on-site emissions produced from 2010 to 2015 (Table 3). Upstream emissions from production of grid electricity and fossil fuels used accounted for 55% of the emissions resulting from all forest operations and wood product manufacturing (Table 3).

Wood product C dynamics for SFJ and hardwood (Figure 4A and C) differed because of the proportion of C allocated to wood and paper products in years 2010–2015, with 87% of total hardwood harvest destined for pulp mills versus only 34% for SFJ. When all storage pools (lumber, paper, and landfill) and landfill emissions were accounted for, wood products manufactured from SFJ roundwood in years 2010–2015 (including bark) remained a net sink of CO_2e 100 years after manufacturing (Figure 4A). In contrast, hardwood roundwood was forecast to become a net source of CO_2e 50 years after manufacturing, because of the high proportion of C allocated to paper, its short in-use lifespan, and associated landfill CH_4 emissions from paper decomposition (Figure 4C). When landfill CH_4 capture was projected to increase (Figure 4B and D), both SFJ and hardwood roundwood harvested in 2010–2015 and manufactured into products remained net sinks of 0.74 and 0.14 t CO_2e, 100 years after manufacturing, per t CO_2e stored in the tree bole.

Products forecast to be produced by JDI during 2010–2015 operation years resulted in an estimated storage of 1.66, 4.21, and 0.58 t CO_2e ha^{-1} in lumber, paper, and landfill pools, respectively, by year 2015 (Figure 5). Upstream emissions to produce grid electricity and fossil fuel used and downstream manufacturing and transport

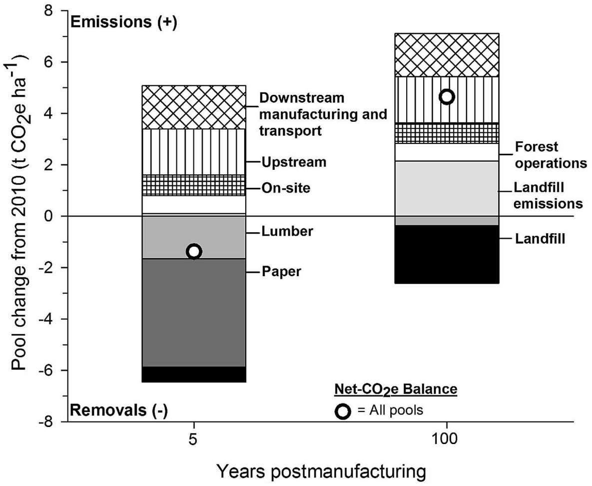

Figure 5. Projected forest product pool (from Figure 4) inventory change and total on-site, upstream (electricity and fossil fuel production/transport), downstream manufacturing and transport (sawlogs, pulpwood, kraft pulp, and rough lumber exported to a third-party manufacturer), and landfill emissions accrued from 2010 to 2015, compared with pool levels 100 years postmanufacturing.

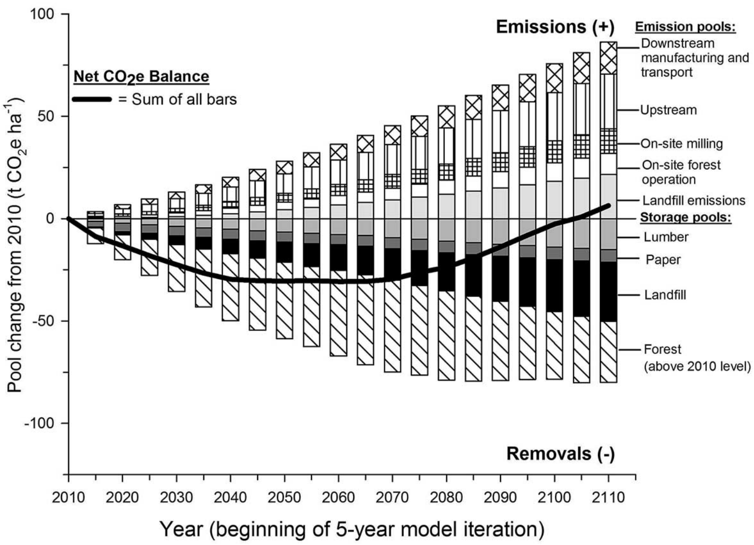

Figure 6. Cumulative CO_2e emissions (above the 0 line) and forest and forest product CO_2e storage change (below the 0 line) projected for 100 years for 2.2 Mha of forest managed by JDI. Emissions include estimates of all on-site manufacturing, upstream (electricity and fossil fuel production/transport), downstream manufacturing and transport (sawlogs, pulpwood, kraft pulp, and rough lumber exported to a third-party manufacturer), and landfill emissions. Removals include estimates of forest and forest product C stock change above 2010 levels expressed in CO_2e.

emissions between 2010 and 2015, accounted for 36 and 33%, respectively, of total (on-site, upstream, and downstream) emissions (Figure 5). Landfill CH_4 and N_2O emissions ("Landfill emissions"; Figure 5) were forecast to be only 2% of total emissions from 2010 to 2015 because a relatively small amount of product C would be transferred into the landfill pool by 2015, and it takes 2 and 5 years from the time of paper and wood landfill deposition, respectively, for CH_4 production via methanogenesis to begin (Skog 2008). Projection of these 2010 to 2015 C product pools over 100 years, assuming no additional inputs, would result in the in-use lumber and paper pools declining by 78 and 100%, respectively. For the same 100-year projection period, landfill storage would increase by 3.6 times to 2.09 t CO_2e ha^{-1} as lumber and paper were disposed of (Figure 5). By 2015, collective storage and emissions pools resulted in a sink of 1.38 t CO_2e ha^{-1} and by 2110 (100 years postmanufacturing), this was forecast to increase to a source of 4.64 t CO_2e ha^{-1} as wood C storage declined and landfill CH_4 emissions accrued (Figure 5).

Projected C Storage Changes and GHG Emissions over 100 Years for Baseline Case

Our third step estimated the baseline scenario C storage changes over 100 years including forest and wood products, emissions from making products, and emissions in landfills as products are disposed of. Forest C storage was projected to increase by 44.9 t CO_2e ha^{-1} from 2010 to 2070 and decline slowly through 2110 (Figure 6). This forest growing stock increase, largely a function of a relatively young initial forest age class structure combined with continued tree planting, was projected to permit sustainable SFJ harvest increases above the current level by 23% after 2045 and by 50% after 2070. Projected harvest increases were forecasted by 2110 to reduce the peak forest C stock level reached in year 2070 by one-third (Figure 6). Cumulative emissions through 2110 included 12% from forest operations, 31% from electricity generation and fuel inputs, 14% from on-site transportation and manufacturing, 18% from transportation and manufacturing of unfinished JDI wood products to final products, and 25% for landfill CH_4 (Figure 6). By 2110, the baseline management strategy resulted in cumulative emissions of 86.3 t CO_2e ha^{-1} (positive values, Figure 6), or a net source of 6.4 t CO_2e ha^{-1} when C uptake by forests and forest product pools are included (solid line, Figure 6).

Projected C Storage Changes and GHG Emissions over 100 Years for Alternate Scenarios

We evaluated four alternate scenarios in which changes were made to the baseline case. Scenario 1, which assumed that landfill CH_4 capture rates would increase from 49 to 90% by year 2040, projected a cumulative net reduction to baseline emissions of 9.2 t CO_2e ha^{-1} (short dash line, Figure 7) by year 2110. Fifteen percent of the decreased emissions (increased net storage) resulted from displaced US grid emissions (with CH_4 burned for energy) and the remainder from decreased landfill CH_4 emissions. Scenario 2, assuming that the NB grid electricity source was 100% hydro, was projected to reduce cumulative emissions by year 2110 by 27.8 t CO_2e ha^{-1} and increase the net C sink by 21.4 t CO_2e ha^{-1} compared with

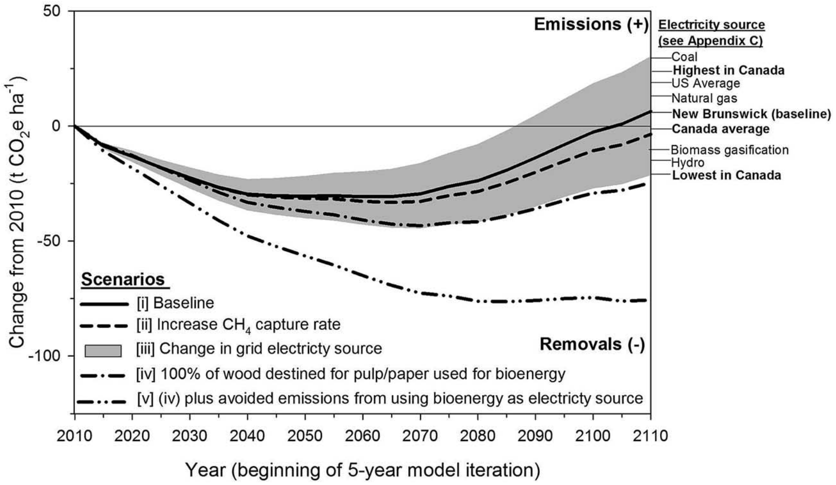

Figure 7. Net GHG emissions attributed to the baseline scenario [i], relative to 2010 levels, and in comparison with consequential effects of increased landfill CH_4 capture [ii], assuming a variety of grid electricity sources [iii], redirection of wood destined for pulp and paper to electricity generation excluding [iv] and including [v] displacement of NB grid emissions.

the baseline scenario (Figure 7). Scenario 3, assumed to divert wood and wood waste from pulp and paper to a gasifier for electricity generation, was projected to reduce emissions by 82.1 t CO_2e ha^{-1}, displace 220 million MWh of grid electricity, and increase the net C sink by 75.6 t CO_2e ha^{-1} by year 100 (dot-dash line, Figure 7). This scenario modified the system boundary to include fossil electricity production and included a reduction in fossil emissions due to displacement of fossil electricity by biomass CH_4 electricity. Scenario 4, assuming no harvesting, no products made, and nonrenewable product replacement of solidwood products, projected that the current relatively young forest with many planted stands would sequester 0.852 t C ha^{-1} $year^{-1}$ into the forest C pool from 2010 to 2055, compared with a baseline of 0.237 t C ha^{-1} $year^{-1}$. As stands matured, C sequestration was projected to slow to 0.136 t C ha^{-1} $year^{-1}$ from 2055 to 2110. With no harvest, the forest pool was projected to store 5.6 times more C than the baseline scenario after 100 years, and the total change in net C storage, without extra emissions due to nonrenewable production, was projected to result in a sink of 168.3 t CO_2e ha^{-1} by 2110. After subtraction of the extra emissions required to produce nonrenewable structural products in place of JDI lumber that would no longer be manufactured, net storage was estimated to decrease by 96.9 t CO2e ha^{-1} compared with the no management scenario, reaching a net sink of 71.5 t CO_2e ha^{-1} in year 2110. Estimation of leakage (replacement of reduced JDI forest products by increased production of products from other lands) emissions under scenarios 3 and 4 could be approximated by multiplying the difference in net GHG balances between baseline and alternate scenarios by the assumed leakage proportion (not estimated here), which assumes that the substitute forest product GHG emissions are proportional per unit of production to JDI operations.

Discussion

GHG Emissions Associated with Wood Product Manufacturing

When the potential of using forests and wood products to reduce atmospheric GHG emissions is evaluated, long-term C storage fate of lumber and paper products along with associated manufacturing emissions must be included. We determined that 22 kg of CO_2e were emitted per 1 m^3 of wood delivered to the mill gate. Based on fossil fuel consumption and grid electricity production, processing 1 m^3 of wood through a JDI sawmill would add an additional 53.6 kg CO_2em^{-3} or 2.4 times more emissions, whereas processing 1 m^3 of wood through a pulp mill would add 872.8 kg CO_2em^{-3} or roughly 16 times more emissions than processing through the average JDI sawmill.

The ratio of GHG storage or emission displacement attributed to forest products compared with the emissions resulting from production or decomposition of those products could be a good index for evaluating the merit of alternative GHG mitigation options. A ratio of 1 would indicate that C storage in forests and wood products would be equivalent to GHG emissions produced throughout the accounting time period. Ratios above and below 1 would suggest a sink and a source, respectively. After 100 years, the baseline forest product storage/emission ratio in this study was 0.58, because emissions were greater than projected C storage. The C storage/emission ratio would increase to 0.6 if landfill CH_4 capture was increased from 49 to 90% by 2040, to 0.84 or 0.33 if JDI mill electricity sources were switched to hydro or coal, respectively, or to 2.7 if wood destined for pulp and paper was redirected for bioenergy. Although implementation of these alternative scenarios may not be feasible due to current/future world fiber demands and electricity production infrastructure, they do illustrate the sensitivity and magnitude of effects for incremental shifts toward producing less GHG emission-intensive forest products through alternative manufacturing strategies.

Net GHG Emissions with and without JDI Forest Product Production

Projection of a no harvest or management scenario provides a reference point to consider the impact of increasing or decreasing forest product production on C stock changes and is required for consideration of other factors such as substitution, leakage, and natural disturbance that influence LCA results. Scenario 4, with no harvest, generated 131.1 and 168.3 t CO_2e ha^{-1} of potential GHG offsets (increased C storage) over 50 and 100 years, respectively. In comparison, the most GHG-efficient forest product strategy explored (pulp/paper biomass redirected toward electricity generation) was projected to yield 34.3 and 69.3 t CO_2e ha^{-1} of potential GHG offsets over 50 and 100 years, respectively. Comparing forest C change for the no harvest scenario with that for the baseline case may suggest that projected GHG offsets would be higher for the unharvested forest; however, the higher C storage is probably overstated because this forest has an increased risk from natural disturbance. In addition, the no harvest scenario needs to include estimates of increased emissions to produce substitute products if JDI does not produce them. Most C offset protocols reduce eligible forest C credits by 0–43% to account for leakage, potential errors in inventory or modeling, and risk of natural disturbances (Galik et al. 2009). Spruce budworm (*Choristoneura fumiferana*

Clem.) outbreaks occur every 30–40 years in this region and kill about 80% of balsam fir and 40% of spruce (MacLean 1980). In past outbreaks, these impacts have been greatly reduced through aerial applications of insecticide; however, this treatment would not be economically viable without a forest product sector (Chang et al. 2012). Spruce budworm was projected to shift forests in eastern Quebec from a C sink to a source (Dymond et al. 2010). Future spruce budworm outbreaks under climate change are predicted to be approximately 6 years longer with an average of 15% greater defoliation (Gray 2008).

If we assume that leakage is nil, that demand for solidwood products or alternatives does not decline, and that JDI structural wood products would be replaced by nonrenewable sources made elsewhere, the net GHG storage under the no management scenario would be reduced by 25 and 54% over 50 and 100 years, respectively, compared with projections excluding product substitution.[4] Specific substitution value estimates are uncertain because they require assumptions about how products would be replaced. The 2.5 times higher forest C stocks under the no harvest compared with the baseline scenario in year 2110 would be at risk to losses from natural disturbances (Kurz et al. 2008). Most literature on GHG mitigation through forest management concludes that either forest conservation or a high-output forest product strategy is preferred. The manufacturing fate of wood products, natural disturbances, and associated avoided emissions from product substitution all significantly affect conclusions about which management strategies produce optimal net GHG storage levels. Although future market shifts may lead to changes in infrastructure, energy sources, and product mix, the modeling framework presented here is amenable to analyze the effects of and perhaps contribute to decisions about such structural changes in the wood products industry.

Conclusions

The net GHG balance of all forest, products, and emissions for a 2.2 Mha landbase forecast over 100 years yielded a sink of 30.7 t $CO_2e\ ha^{-1}$ at year 50, but because of projected harvest increases, emissions exceeded sequestration by year 85, resulting in a source of 6.4 t $CO_2e\ ha^{-1}$ by year 100. Paper products had high energy demands and emissions during manufacturing, short in-use life, and large emissions from landfill decomposition. Because the energy, wood, and paper product sectors are so intertwined, inclusion of all sectors is necessary to determine the overall GHG footprint of forest product production and to decide on meaningful forest management strategies to reduce GHG emissions. In evaluation of a range of strategies from no harvesting to sequestering C in forest products for GHG reduction, the probability of natural disturbance, leakage, and product substitution must be considered. Natural disturbance from fire, spruce budworm, or other insect outbreaks is a substantial risk associated with maintaining large C stocks in forest, and this risk should be included in analyses. Our results suggest that depending on factors such as disturbance risk, products produced, and grid electricity emissions, intensive forest management to produce a sustainable long-term supply of solidwood products and biofuel may result in a GHG mitigation potential similar to that when forests are allowed to grow unmanaged, while providing forest products that produce societal benefits.

Endnotes

1. Data from Environment Canada (2010a).
2. Note that in Appendix B, we assumed a biomass gasification operation to be a conservative approximation of a landfill biogas operation because of the lack of available life-cycle estimates for this operation at the time of this study.
3. Unless otherwise stated, all references to "emissions" refer to GHGs expressed in CO_2e units.
4. This is based on assuming an average lumber products substitution value of 2.1 t C per t C (Sathre and O'Connor 2010). This substitution value may be low or high because of differences in accounting assumptions between static LCA cited in Sathre and O'Connor (2010) and our dynamic LCA.

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Appendix A: Factors used to calculate on-site and upstream emissions in this study.

Source	Factor	Reference
On-site emissions		
Diesel (heavy equipment)	3.79 kg CO_2e L^{-1}	Intergovernmental Panel on Climate Change (IPCC) (2006)
Diesel (transport)	3.46 kg CO_2e L^{-1}	IPCC (2006)
Gasoline	2.36 kg CO_2e L^{-1}	IPCC (2006)
Jet A1 fuel	2.25 kg CO_2e L^{-1}	International Carbon Bank and Exchange (2000)
Natural gas	1.96 kg CO_2e m^{-3}	Environment Canada (2010b)
Heavy fuel oil	3.12 kg CO_2e L^{-1}	Environment Canada (2010b)
Propane	1.51 kg CO_2e L^{-1}	Environment Canada (2010b)
Black liquor combustion	1.4 kg CO_2e kg^{-1}	Environment Canada (2010b)
Woodwaste combustion	0.95 kg CO_2e kg^{-1}	Environment Canada (2010b)
Pulp transport to non-NB tissue mills (per km)	0.017 kg CO_2e t^{-1}	IPCC (2006)
Tissue roll transport to converting facility (per km)	0.16 kg CO_2e t^{-1}	IPCC (2006)
Upstream emissions		
NB grid electricity	0.46 kg CO_2e kWh^{-1}	Environment Canada (2010b)
US national grid electricity average	0.63 kg CO_2e kWh^{-1}	EPA (2010)
Diesel/gasoline	0.058 kg CO_2e L^{-1}	DeLuchi (1991)
Natural gas	0.0012 kg CO_2e L^{-1}	DeLuchi (1991)
Nitrogen fertilizer	5.88 kg CO_2e kg^{-1}	Liska et al. (2009)
Downstream emissions		
Average barge transport (per km)	0.014 kg CO_2e t^{-1}	Kent Lines (2011)
Rough lumber/roadside chips transport (per km)	0.07 kg CO_2e m^{-3}	IPCC (2006)
Lumber manufacturing	146.99 kg CO_2e m^{-3}	Bergman and Bowe (2010)
Processing rough lumber[a]	12.18 kg CO_2e m^{-3}	Hubbard and Bowe (2010)
Kraft production from raw material[b]	422.52 kg CO_2e t^{-1}	Francis et al. (2002)
Paper product production from pulp[c]	493.04 kg CO_2e t^{-1}	Integrated Pollution Prevention and Control (2000), Françis et al. (2002)

[a] Used on-site boundary of study with additional accounting of purchased electricity emissions for 48.4 MJ of energy used per m^3 using NB's average emissions (460 g CO_2e kWh^{-1}).
[b] Adapted to assume NB's average grid electricity values (Environment Canada 2010a).
[c] Aggregated value assuming an equal one third production of specialty paper (Integrated Pollution Prevention and Control 2000), newsprint, and cardboard (Françis et al. 2002). Excludes pulp production emissions.

Appendix B: Postdisposal fates of C stored in lumber and paper products used in this study.

Product state	Pool allocation	Amount	Reference
Disposed lumber	Recycled	9.0%	Skog (2008)
	Combusted for energy or waste[a]	24.0%	
	Landfilled nondecaying	51.6%	Smith et al. (2006); their Table D4
	Landfilled decaying	15.4%	Smith et al. (2006)
	Decay half-life	29 yr	Skog (2008)
Disposed paper	Recycled	41.5%	Skog (2008)
	Waste from recycling[b]	8.5%	Cote et al. (2002)
	Combusted for energy or waste[c]	19.0%	
	Landfilled nondecaying	13.6%	Skog (2008)
	Landfilled decaying	17.4%	Smith et al. (2006)
	Decay half-life	14.5 yr	Skog (2008)
Decayed aerobically	CO_2	100%	National Council for Air and Stream Improvement, Inc. (NCASI) (2004)
Decayed anaerobically[c]	CO_2	50%	NCASI (2004)
	CH_4	50%	NCASI (2004)
CH_4 from landfill anaerobic decay	Landfill CH_4 captured[d]	36.7%	EPA (2002)
	Noncaptured CH_4 converted to CO_2 by bacteria in soil cover	36.5%	Chantona et al. (2009)
Global warming potential assumed[e]	CO_2e	1	Environment Canada (2012)
	N_2O	310	Environment Canada (2012)
	CH_4	21	Environment Canada (2012)
CH_4 capture energy, bioenergy production	Energy potential	15.47 kWh kg^{-1}	Wainger (2008)
	Conversion efficiency	30%	Wainger (2008)
CH_4 capture energy	Energy potential	6,111 kWh oven dry ton^{-1}	Ince (1977)
	Conversion efficiency	37%	Mann and Spath (1997)
	Operation emissions[f]	45.6 g CO_2e kWh^{-1}	Spitzley and Keoleian (2004)

[a] Non-landfilled or recycled lumber or paper products were assumed to be combusted for energy or waste.
[b] Assumed that 17% of scrap paper recycled was lost to waste during the conversion process (Cote et al. 2002).
[c] Anaerobic conditions, favorable for methanogenesis, were assumed to develop 2 and 5 years postdisposal for paper and lumber products, respectively (Skog et al. 2008).
[d] Assumes that 49% of US landfills have CH_4 capture systems with an average capture efficiency of 75% (EPA 2002).
[e] Amount relative to 1 g of CO_2e (12/44 g of C) stored in the fuel.
[f] Assumed that the CH_4 capture process generated the same GHG emissions per kWh as the gasification process for bioenergy.

Appendix C: Electricity generation emission estimates used in Figure 7.

Power source	Studies reviewed	Electricity generation emissions			Reference
		Average	Lower bound	Upper bound	
		($g\ CO_2e\ kWh^{-1}$)			
Wind	2	2.1	1.7	2.5	Spitzley and Keoleian (2004)
Nuclear	1	19			Spitzley and Keoleian (2004)
Hydro[a]	1	26.1			Spitzley and Keoleian (2004)
Gasification	4	45.6	38.9	52.3	Spitzley and Keoleian (2004)
Wood pellets	1	104.5	21.2	187.7	Spitzley and Keoleian (2004)
Solar	3	57.5	43.7	71.2	Spitzley and Keoleian (2004)
Natural gas	1	504			Spitzley and Keoleian (2004)
Coal and coal/biomass	5	899	758	1,040	Spitzley and Keoleian (2004)
New Brunswick		460			Environment Canada (2010a)
Quebec[b]		2			Environment Canada (2010a)
Alberta[c]		200			Environment Canada (2010a)
Canada average		880			Environment Canada (2010a)
US average		630			EPA (2010)

[a] Accounts for emissions associated with construction of the dam and tree decay from the flooding of the head pond.
[b] Lowest provincial average in Canada (Environment Canada 2010b).
[c] Highest provincial average in Canada (Environment Canada 2010c).