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Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence

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ABSTRACT

This paper examines the energy and carbon balance of two residential house alternatives; a *typical* wood frame home using more conventional materials (brick cladding, vinyl windows, asphalt shingles, and fibreglass insulation) and a similar wood frame house that also maximizes wood use throughout (cedar shingles and siding, wood windows, and cellulose insulation) in place of the more typical materials used – a *wood-intensive* house. Carbon emission and fossil fuel consumption balances were established for the two homes based on the cumulative total of three subsystems: (1) forest harvesting and regeneration; (2) cradle-to-gate product manufacturing, construction, and replacement effects over a 100-year service life; and (3) end-of-life effects – landfilling with methane capture and combustion or recovery of biomass for energy production.

The net carbon balance of the wood-intensive house showed a complete offset of the manufacturing emissions by the credit given to the system for forest re-growth. Including landfill methane emissions, the wood-intensive life cycle yielded 20 tons of CO_2e emissions compared to 72 tons for the typical house. The wood-intensive home's life cycle also consumed only 45% of the fossil fuels used in the typical house.

Diverting wood materials from the landfill at the end of life improved the life cycle balances of both the typical and wood-intensive houses. The carbon balance of the wood-intensive house was 5.2 tons of CO_2e permanently removed from the atmosphere (a net carbon sink) as compared to 63.4 of total CO_2e emissions for the typical house. Substitution of wood fuel for natural gas and coal in electricity production led to a net energy balance of the wood-intensive house that was nearly neutral, 87.1 GJ energy use, 88% lower than the scenario in which the materials were landfilled.

Allocating biomass generation and carbon sequestration in the forest on an economic basis as opposed to a mass basis significantly improves the life cycle balances of both houses. Employing an economic allocation method to the forest leads to 3–5 times greater carbon sequestration and fossil fuel substitution attributable to the house, which is doubled in forestry regimes that remove stumps and slash as fuel. Thus, wood use has the potential to create a significantly negative carbon footprint for a house up to the point of occupancy and even offset a portion of heating and cooling energy use and carbon emissions; the wood-intensive house is energy and carbon neutral for 34–68 years in Ottawa and has the potential to be a net carbon sink and energy producer in a more temperate climate like San Francisco.

1. Introduction

North American residential construction is dominated by the ubiquitous "stick framing" sheathed in plywood or OSB. Wood is also used, to a lesser extent, for wall cladding, roofing, and in window frames. The lower cost or maintenance requirements of brick cladding, vinyl siding, vinyl window frames, and asphalt roofing shingles have led to the abandonment of wood use in exterior applications. The green building movement has created a renewed interest in maximizing the use of wood products based on research demonstrating that wood products require fewer non-renewable fuels and emit fewer greenhouse gases than alternative materials over their life cycles. This research has generally been conducted on three distinct but interrelated systems that comprise the life cycle of wood products and buildings.

- *Forest sequestration*: Over the service life of a durable wood product, the forest from which the wood originated is replaced

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by a younger, faster growing forest that regenerates and sequesters additional carbon [21]. On average, North American forests that are left unlogged are subject to natural disturbance within the service life of a durable wood product that would have otherwise been produced. Thus, the wood removed and sheltered from natural cycling is counted as a carbon credit granted to the forest equal to the amount of carbon dioxide consumed during growth.

- *Product system*: Wood building materials typically require less energy to manufacture and generate fewer greenhouse gases than alternative building materials used in similar applications [11,23,25,33]. The wood product life cycle also generates a surplus of wood waste that is used as fuel and as a low embodied energy material input into other products.
- *End of life*: Post-consumer wood products retain many valuable properties and may be downcycled into pulp and paper, or burned as a fuel, offsetting virgin material and fossil fuel, respectively. In North America, most wood waste is sent to a landfill, where the majority of solid wood remains undecayed due to the presence of lignin and imperfect conditions for microbacteria [26], with the remainder anaerobically decomposed into methane and carbon dioxide, called landfill gas. Landfill gas is increasingly being captured and used as a fuel.

In this research, a life cycle assessment was completed on two residential houses, one constructed of the most commonly used materials and the other maximally using wood. The LCA included the three systems; forest sequestration, product system, and end of life.

By demonstrating that the forest from which the wood was initially derived would likely have been replaced naturally had it not been logged, the biogenic carbon emissions are offset and have no net effect. This is based on the conclusion that leaving the forest unlogged would have resulted in the conversion of sequestered forest carbon into carbon dioxide through fire or aerobic decomposition. Thus, the carbon balance over the life cycle is the sum of fossil fuel-based emissions from manufacturing, construction and product replacement as well as the methane released from the landfill. Permanently sequestered carbon is an anthropogenic credit to the life cycle.

To account for the feedstock energy present in post-consumer wood, the product system of the typical house was expanded to include the generation of energy from conventional fossil sources such that the two functional units describe the same functionality, housing and energy. The avoided fossil combustion is accounted as another anthropogenic credit to the life cycle.

1.1. *Previous forest product carbon and energy accounting*

The number of life cycle assessment studies comparing wood products with alternatives in construction has been so numerous that four separate literature reviews have been completed in recent years on the topic [11,23,25,34]. The consensus finding is that wood products are less energy intensive and reliant on fossil fuels and consequently produce less greenhouse gases than alternative building material over their life cycle. However, a high degree of variability is noted depending on how wood is treated at the end of its life cycle and the potential of methane emissions when wood is disposed in landfills [2,23,25]. The greatest potential for preventing wood related carbon emissions was found in scenarios in which forests were managed sustainably (where net carbon was neutral over time), wood products substituted for alternative materials were having a higher embodied energy, and wood wastes were recovered and used to generate energy which in turn substituted for fossil fuels [25].

1.1.1. *Product system*

Life cycle assessments of wood products have demonstrated that manufacturing wood building products typically requires less energy than alternative building materials and that this leads to lower environmental impacts when the entire life cycle is considered [2–5,7,11,13,18,22,29,34]. Life cycle inventory values, the tabulation of material/energy use and emissions that are the precursor to life cycle assessment, have been generated for numerous wood products, including milled and dried softwood lumber [3], sheathing products like OSB and plywood [3], softwood window frames [24], cedar siding [18], and cedar shakes and shingles [19]. These LCIs have been used in direct greenhouse gas comparisons of wood products against those of alternative materials to show that wood causes less GHG emissions than concrete and steel as a framing material [2–5,7,13,22,29], less than vinyl as siding [18], less than fibreglass as insulation [18], and less than PVC or fibreglass as a window frame material [24]. When wood is used in multiple applications the benefits are compounded [18,25].

1.1.2. *Forest and product system*

In addition to requiring less manufacturing energy, wood's forest origins also create the potential to reduce the net greenhouse gas effect through carbon sequestration [2,10,13,21,25,27,28]. During the service life of the house and afterward, when the demolition debris is taken to a landfill, the forests from which the wood materials originated regenerate and remove more carbon from the atmosphere.

Fixing biogenic carbon in a durable good causes a net atmospheric reduction in two ways. First, the timely removal of carbon from the forest eliminates the likelihood that the forest carbon stock would be emitted during a natural disturbance. Additionally, logging a mature forest converts it from a forest with a lower growth/decay ratio into a faster growing and carbon fixing forest [21]. Fig. 1 illustrates the growth (I and II), steady state (III), and eventual decline of biomass as a forest matures (IV).

Removing trees late in phase II, after growth has slowed, and reinitiating phase I create an atmospheric carbon reduction as the forest returns to the pre-harvest level. Considering this carbon reduction as a flow from the biosphere into the system boundaries in a life cycle assessment requires considering the alternative fate of the forest had it not been logged. Had no extraction taken place, the biomass would have eventually reached the decline stage or been disturbed naturally. The service life of the building in which the carbon is sequestered is not indefinite, however, and thus the fate

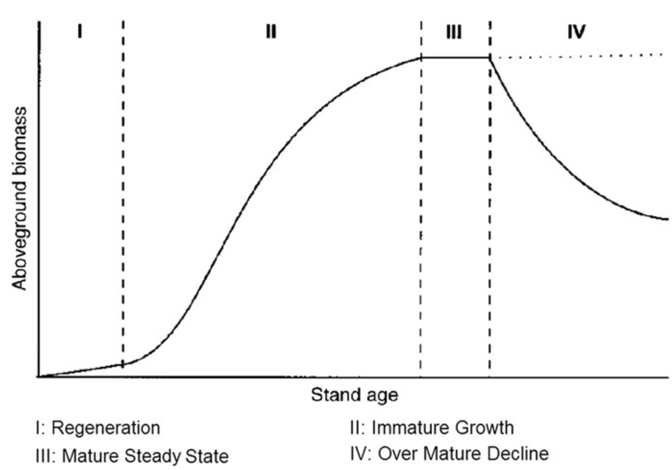

Fig. 1. Growth characteristics for the four phases of forest maturity in carbon budget model for Canadian forest [17].

of the carbon in the wood must be tracked further to the processes that occur at the end of life to determine the permanent anthropogenic effect.

Perez-Garcia et al. [21] considered the potential effects to the total carbon balance of a forest and related product pools. In their analysis they considered the forest carbon balance in a managed forest, logged in 80-year rotations in addition to the carbon sequestered in durable products and the virtual carbon pool of prevented emissions caused by specifying wood over more energy-intensive building materials. Fig. 2 shows the results of their simulation.

After two rotation cycles, 160 years, the net carbon pool is equivalent to 700 mtons/ha while the sustainably managed forest contains an average of 125 mtons (ranging from 50 to 200 tons within each harvest cycle). Had the forest not been logged, it would have continued to grow past the 80-year harvest point but would have eventually reached maturity, decline, or been naturally disturbed. Thus, the accumulation over time in the three pools leads to the conclusion that forest management that includes logging effectively shelters the carbon in a mature forest from natural disturbance, its eventual fate otherwise.

1.1.3. Product, forest, and fossil fuel substitution

The wood product life cycle also results in the production of wood wastes that have an energy value. The utilization of wood as a fuel substitutes for non-renewable fuels and replaces the carbon emitting cycle with a closed loop one that recaptures the carbon emitted from wood combustion through forest re-growth [26].

Eriksson et al. [10] explored a scenario in which the wood is first used as a durable product and is then burned at the end of its useful life, substituting for both energy-intensive building materials and for fossil fuels. In this case the wood product system includes an expanded system boundary that incorporates the fuel function. This system boundary expansion is matched by expanding the system boundary of the alternative building material to include a second life cycle of fossil fuel use beyond that which is directly used to manufacture the product.

In their example, shown in Fig. 3, the forest is managed and fertilized, and the stumps and debris are also removed and burned with energy recovery, avoiding combustion of the comparable heat value of coal. The example in Fig. 3 shows that wood products not only benefit from their lower embodied energy and by removing material from potential natural disturbance, but the wood product life cycle also produces carbon-neutral fuel that avoids the use of fossil fuels and the liberation of the carbon they contain.

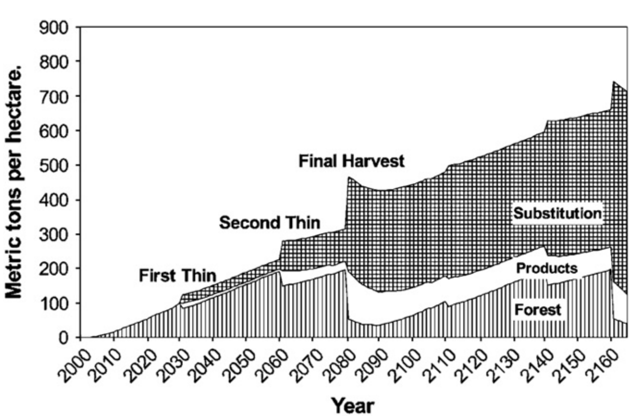

Fig. 2. Carbon pools related to forest growth and product substitution for an 80-year harvest cycle [21].

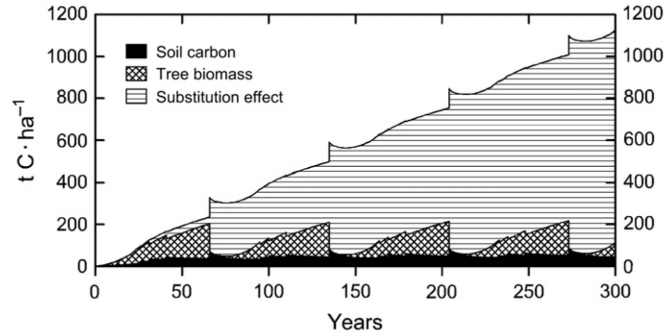

Fig. 3. Carbon pools related to forest growth, product substitution, and maximal fuel substitution for an 80-year harvest cycle, coal as the substituted fuel [10].

2. Methods

In this research, the three subsystems of the life cycle have been studied individually and the results combined to create a net carbon balance and non-renewable fuel requirement balance for both a typical North American home and one that substitutes wood products for conventional materials where possible. Three distinct methodologies were employed to address the requirements of modelling the three systems.

- *Forest sequestration*: North American forest statistics are presented to justify the conclusion that logging the forest removes carbon that would have otherwise been emitted naturally.
- *Product system*: The ATHENA Impact Estimator was used to model the life cycle of the two houses from the point of resource extraction to disposal at the end of life.
- *End of life*: Two scenarios are modelled; one in which the products are disposed in a landfill that utilizes average methane capture technology; and another in which the wood is recovered for use as a fuel.

The following conventions were followed in the carbon and energy accounting. Carbon emissions to the atmosphere were assigned a positive value and a negative value to flows out of the atmosphere into biomass. Fossil fuel accounting assigns a positive value to the use of these finite resources, with a negative value used to account for a prevention of their use. This convention was followed as a minimization of either value is typically the goal of the environmentally conscious, despite one representing net flow to the biosphere (atmosphere) and the other a flow from the biosphere (terrestrial resource stocks). Fig. 4 shows the subsystems

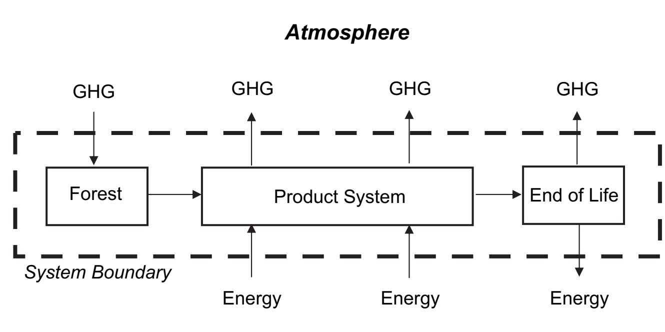

Fig. 4. Three systems considered and their relationship with the atmosphere and resource pools.

that were examined and the flows into and out of the system boundaries.

Carbon accounting was conducted by converting all flows to their carbon dioxide equivalent value (CO_2e). Thus, all flows of biomass carbon out of the forest and from biomass back to the atmosphere were multiplied by a factor of 44/12, the mass ratio of CO_2 to C. All flows of methane to the atmosphere were scaled based on the mass ratio 16/44, the mass ratio of CH_4 to CO_2, and the characterization factor 25, the greenhouse gas forcing of CH_4 relative to CO_2 [14].

Energy accounting was conducted based on the higher heating value (HHV) of fossil fuels that is provided with the USLCI database [32]. All energy sources were converted to a common unit (GJ) despite differences in the utilities of the different fuels. For instance, natural gas is suitable as a space heating fuel in dense residential areas while coal and wood are deemed less desirable in these applications. In North America, all three of these fuels are suitable to generate electricity and thus biomass substitution was assumed as occurring for this purpose.

Energy substitution offsets the marginal electricity fuels, coal and natural gas, as opposed to fixed assets like hydrodams and nuclear power plants. In Ontario 18% of total electricity generation is provided by coal with 9% provided by natural gas. Substitution of fossil fuel in electricity production was done based on this ratio (2:1). This methodology assumes that different electricity fuels are perfect substitutes for each other (the cross-elasticity of coal to biomass and natural gas to biomass is positive infinity) and thus increasing the biomass supplied results in a functionally equivalent reduction of other fuel use. Forcing post-consumer biomass recovery implies some sort of subsidy as the current average treatment is to deposit the material in the landfill. Additionally, the marginal nature of this analysis means that the results are not necessarily relevant across all scales.

The fuels are assumed to have the following higher heating value (HHV), electricity yield, and subsequent greenhouse gas emissions [32]:

- *Coal*: 24.76 MJ/kg provides 2.27 kWh/kg and causes 1.08 kg CO2e/kWh.
- *Natural gas*: 38.74 MJ/m^3 provides 3.33 kWh/m^3 and causes 0.72 kg CO2e/kWh.
- *Wood*: 23.6 MJ/kg provides 2.17 kWh/kg and causes 0.89 kg CO2e/kWh.

2.1. Forest sequestration

Considering the forest as a supply system, with atmospheric carbon and solar energy as resources and trees as products, brings the flow of carbon into the system boundaries of the life cycle assessment. To include the atmospheric carbon reduction as a net negative in our accounting, the fate of the forest had it not been logged was also considered. If the trees are not realized as products or lost to natural disturbance, the forest reaches maturity and eventually becomes a carbon emitting forest as was noted in Fig. 1. This tendency is illustrated by examining the carbon content in various age classes of Canadian forests as is shown in Table 1.

In 1994, 92% of Canadian forests were younger than 160 years old and 70% were less than 100 years old, with an average age of 81.5 years [6]. As is shown in Table 1, net carbon removed from the atmosphere and fixed as biomass declines in the 80–99-year-age class to 2 tons carbon/ha from 25 tons carbon/ha during the 60–80-year-age class. Thus, it may be reasoned that by 1994 the average Canadian forest had begun to enter the relatively steady state mature phase described in Fig. 1. Had the trees in the 60–99-year-age class, comprising 25% of standing forest area, been logged, this would have prevented their likely mortality between years 100–160 and the eventual loss of carbon that occurs after year 160 even if the trees survive.

Since the 1994 inventory, the frequency and extent of natural disturbances have grown, while harvest levels have remained relatively unchanged. Fig. 5 shows the area of Canadian forest lost annually to natural disturbance (ranging from 47 to 243 million ha) and harvest, around 1 million ha. The increase in disturbance levels has caused volatility in the forest carbon balance as fires remove much of the carbon stored in organic matter and insects kill standing timber that decays in subsequent years. Recent forest carbon balances exemplify this volatility as Canadian forests have recently ranged from a net sink of −151 Mt CO_2e in 1992 to a net source of 155 Mt CO_2e in 1995 [9].

The increase in natural disturbances lends credibility to the argument that the carbon removed from the forest and sheltered in products should be assigned as a credit to the product system. Assuming a 100-year service life for a house, the forests from which the wood products came will regenerate and on average reach the pre-logging carbon level while the products are still in use. Had the forest not been logged, the carbon contained in the standing trees would have likely been emitted to the atmosphere, or otherwise reached the phase of over-maturity and net carbon decline as described in Fig. 1 and exemplified in Table 1.

It must also be noted that while logging a forest does not have an identical effect to short-term forest soil carbon as natural disturbances, the differences between the two scenarios are erased over time. A recent literature review was completed on this topic and it was determined that long-term soil carbon levels do not decrease in a statistically significant manner as a result of fire or logging [15] despite some variation in the 73 studies they considered.

The system under consideration in this LCA will be credited a carbon reduction for the wood contained in the house as the forest is assumed to regenerate completely to pre-harvest carbon levels. The carbon in the product becomes a baseline from which decomposition and combustion emissions may be subtracted from the forest carbon credit to determine the net flow of biosynthetically fixed carbon over the life cycle. Thus, in Section 3, the forest sequestration values are calculated directly from the wood materials used over the life cycle of the house.

2.2. Product system

The Athena Institute completed a prior study on the life cycle impacts of an R2000 house, an example of standard Canadian building practice [20]. Bills of materials were generated for two cases: an R2000 reference house of typical materials located on the National Research Council of Canada's campus in Ottawa; and an alternative wood-intensive case whereby wood products were specified as roofing shakes, window frames, cladding, and cellulose insulation. The varying specifications for the houses are shown in Table 2. The Athena Institute's Impact Estimator (IE), v4.0, was used to generate the bill of materials for the two house design scenarios (www.athenasmi.org) and to relate this to the LCI of each component over the life cycle.

The Athena Institute has developed LCI data on typical North American construction materials that integrate the USLCI's energy production modules [32] in order to conduct whole building LCA. The IE software draws on region-specific maintenance schedules and supply chain characteristics for 12 geographic regions; this study utilized data specific to the Ottawa location. The modelling was based on a 100-year service life with average maintenance schedules typical for Ottawa's climate. A similar house constructed in Vancouver was also analyzed with no significant difference

Table 1
Carbon sequestration of Canadian forests by age class in 1994 [6].

Forest area			Biomass		
Age class (years)	Million ha	%	Mt C	Average t C/ha	Change within age class t C/ha (calculated)
0–19	80.43	22.1	178.9	2.0	
20–39	47.74	11.8	381.9	8.0	6.0
40–59	44.01	10.9	1320.2	30.0	22.0
60–79	49.82	12.3	2740.0	55.0	25.0
80–99	51.31	12.7	2924.9	57.0	2.0
100–119	34.66	8.6	2045.2	59.0	2.0
120–139	37.46	9.3	2322.3	62.0	3.0
140–159	16.17	4.0	1115.6	69.0	7.0
160+	33.63	8.3	1325.5	40.2	(28.2)
Total	404.23	100.0	14,381.4	35.6	

found between the life cycle balances of the homes in the two locations.

Fig. 6 identifies processes and flows that were modelled in the IE. Fuels are used to extract materials, transport them, and manufacture the building materials necessary to construct and maintain the building over its expected 100-year service life.

2.3. End of life

At the end of the home's 100-year service life, North American homes are typically demolished and deposited in landfills. In the landfill, the wood material is buried and a portion of the carbon in the product is converted into two greenhouse gases: carbon dioxide and methane. Modern landfills have rapidly adopted methane capture over the past 10 years, up from 15% in 1998 [27] to 50% in 2008 [28]. The major municipal landfills that serve Ottawa have methane capture systems in place and thus it was assumed that the demolition waste is disposed of in such a landfill.

Wood's lignin content and imperfect conditions for anaerobic microbacteria that exist in landfills cause the majority of carbon in wood to remain intact while 24% is converted equally to carbon dioxide and methane [1,8,31]. A portion of the methane that is produced, about 10% [31], is oxidized within the landfill before it reaches the surface. Thus, the composition of landfill gas is 55% CO_2, 45% CH_4 (on a molar basis) when it reaches the surface.

Landfill gas capture systems operate at varying efficiencies. The USEPA estimates that the average landfill gas capture technology results in the capture of about 75% of emitted landfill gas [31] although one empirical study suggests a somewhat lower capture of 35% [30]. Of the 75% that is captured, only 70% is combusted in an industrial turbine to produce electricity. The remaining 30% is flared to eliminate methane but without energy recovery [30]. The LFG that is utilized as fuel has a heating value of 15.8 MJ/kg [33] and reduces demand for equivalent amounts of coal and natural gas that would have otherwise been consumed to produce electricity. The equations defining the conversion of carbon in the landfill are included in Appendix 1.

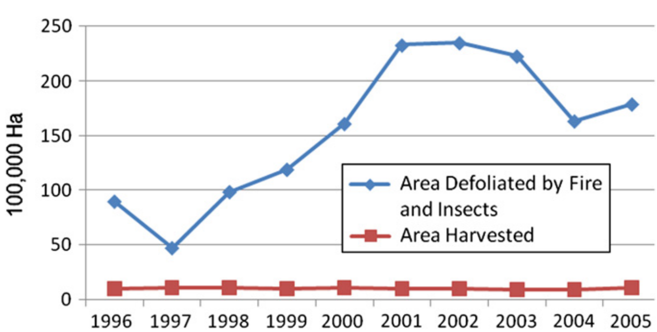

Fig. 5. Source of Canadian forest disturbance between 1996 and 2005.

An alternative scenario was also considered in which wood products were diverted from the landfill and burned in industrial furnaces with heat recovery, a practice that has been proposed by many in North America and has recently become law in the European Union [12]. Burning wood waste prevents the production of methane caused by anaerobic decomposition and essentially mirrors the natural occurrences of the forest system. Thus, the net carbon balance of the forest and combustion is neutral.

The two end-of-life scenarios are represented in Fig. 7. The direct emissions of greenhouse gases are shown as well as those caused by burning landfill gas or biomass as fuel. The fuels produced by the end-of-life scenarios were assumed to be burned in utility boilers to generate electricity. The energy obtained from burning the fuels reduced demand for electricity from other sources, thus substituting for the current marginal fuels used in Ontario electricity generation – coal and natural gas. This effectively expands the system boundary of the home's product system to include the functionality of post-consumer wood and brings fossil fuel electricity production not used directly in the house's life cycle within the system boundary. For illustrative purposes it was assumed that 100% of the wood waste was recovered as potential fuel.

3. Results

3.1. Forest results

The wood-intensive house used over twice the amount of forest products as the typical house, 25.1 tons in the wood-intensive house as opposed to 11.6 tons in the typical house. Scaled based on the carbon content of the wood (approximately 50%, varying by species) and the ratio of carbon dioxide's mass to carbon's (44/12), it was determined that the forests that produced the wood sequestered 18.3 tons of CO_2e in the case of the typical house, and 54.3 tons for the wood-intensive house. These results are shown in Table 3.

The specification of cedar shingles, cedar siding, and wood framed windows in the wood-intensive house, all materials that are periodically replaced over a house's service life, drove the difference between the two designs, as 40% of the wood used in the wood-intensive house went into replacements made after initial construction. Cellulose insulation is included in the carbon credit because the material input is diverted from the waste stream and treated, thus delaying its deposition in the landfill and reducing its decay potential when it gets there.

Table 2
Sample houses specifications.

		Standard	Wood intensive
General		207.4 m^2 Two-story, single-family with full basement	207.4 m^2 Two-story, single-family with full basement
Framing		2″ × 6″ kiln dried softwood studs Studs 16″ O/C	2″ × 6″ kiln dried softwood studs Studs 16″ O/C
Sheathing		9–12 mm softwood plywood	9–12 mm softwood plywood
Interior		12 mm interior gypsum board	12 mm interior gypsum board
Insulation		Fibreglass	Cellulose
Siding	Material Service life	Brick 100 years	Cedar 20 years
Roof	Material Service life	Asphalt w/ felt 25 years	Cedar shingle 35 years
Windows	Frame material Service life	Vinyl 18 years	Wood 18 years

3.2. Product system results

As shown in Fig. 6, burning fuels during the cradle-to-gate manufacturing, construction, and periodic product replacement over the service life of the house caused greenhouse gases to be emitted from the product system. The wood-intensive house required less energy to manufacture the materials used in the initial build and those that were replaced over the service life. The cradle-to-gate manufacture of the wood-intensive house used 55% of the non-renewable fuels of the typical house (536.8 GJ for the wood-intensive house compared to 968.0 GJ for the typical house). The primary difference between the two initial builds was in the use of brick cladding in the typical house and cedar siding for the wood-intensive design. Over the service life of the house the brick was not replaced while the cedar siding was replaced at periodic intervals. The relatively low embodied energy of cedar siding and the other wood based replacement materials netted a reduction of 62% of the fossil fuels used in the vinyl and asphalt replacement materials of the typical house.

As the emissions of greenhouse gases were caused primarily by the fuel combustion, the wood-intensive house generated fewer greenhouse gas emissions than the typical house in roughly the same proportions. The manufacture of vinyl and asphalt does consume some primary fuels that are not combusted, called feed-stock energy; this was accounted for in the fuel use but was not burned and did not generate greenhouse gas emissions. Additionally, manufacturing the concrete foundation, common to both designs, causes significant process emission of carbon not related to fossil fuel use. Thus, while the wood-intensive house used 52% fewer fossil fuels to manufacture, it emitted 33% fewer greenhouse gases in this phase than the typical house.

3.3. End-of-life results

For both the houses, the lowest carbon emissions and fossil fuel use results were achieved by the biomass recovery for energy production as opposed to landfilling with methane gas capture. Burning the biomass substituted for 698.3 GJ of non-renewable fuel for the wood-intensive house and 235.1 GJ for the typical house. The landfill scenario caused a small amount of fossil fuel substitution from the capture and utilization of landfill gas, but was insignificant compared to fuel use in the other life stages.

In the landfill scenario, the wood-intensive house caused greater greenhouse emissions. The wood-intensive house generated more material that could be anaerobically and aerobically metabolized in the landfill, which led to 3 times the direct greenhouse gas emissions by the wood-intensive house in the landfill as compared to the typical house. This resulted in a net difference between the two houses of 11.9 tons CO_2e (the wood-intensive house creating 18.0 tons CO_2e and the typical house generating 6.1 tons CO_2e).

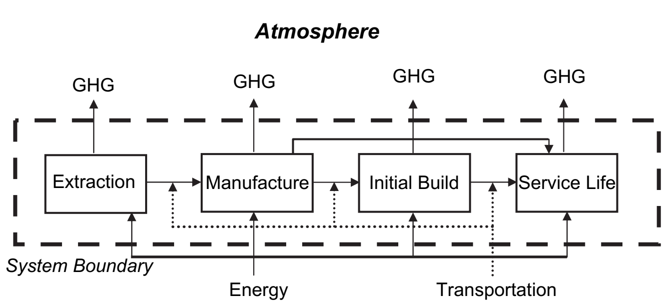

Fig. 6. Product system.

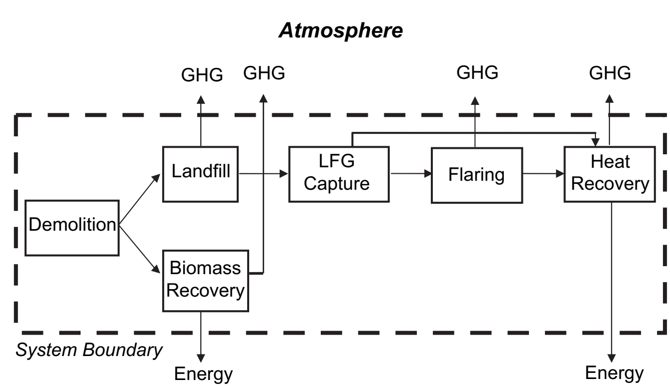

Fig. 7. End-of-life system including landfill and biomass recovery scenarios.

Table 3
Wood use in both sample houses and the assumed forest carbon uptake.

		Wood (tons)		CO_2 uptake (tons)	
		Initial build	Use phase	Initial build	Use phase
Common to both	Small dim, lumber, kiln-dried	4.65		8.53	
	Softwood plywood:(9 mm basis)	3.14		5.76	
	Large dim, lumber, kiln-dried	2.16		3.96	
Wood-intensive only	Cedar wood bevel siding	1.08	4.34	1.99	7.95
	Cedar shingles	2.39	4.43	4.37	8.12
	Wood window frame	0.69	3.13	1.26	5.73
	Blown cellulose (25 mm)	3.59		6.58	
	Typical house	*9.96*		*18.25*	
	Wood-intensive house	*17.70*	*11.89*	*32.46*	*21.81*

Research is currently being conducted in North America and in Europe to develop bioreactors that more efficiently convert biomass waste to fuel and an increase in methane utilization is expected by the time a house currently under construction reaches the landfill. Biomass recovery utilizes technology that is already in place, albeit less popular than conventional demolition and deposition in landfill. In the biomass recovery scenario more carbon is released to the atmosphere but this minimizes the generation of methane and allows greater heat recovery, which substitutes for fossil fuel. The biomass fuel produces less greenhouse gases per kWh than coal, such that the biomass recovery processes netted a carbon reduction for both the typical and wood-intensive houses.

3.4. Cumulative forest, product system, and end-of-life results

The net flows of non-renewable fuels into the system and the net flows of greenhouse gases into the atmosphere are shown in Table 4. The scenario that caused the fewest greenhouse gas emissions (a net reduction of atmospheric carbon) and used the least fuel was the wood-intensive house with biomass energy recovery. In the biomass recovery scenario, the heat value of the wood waste for the wood-intensive house offset 89% of the non-renewable fuel that was used to manufacture the initial build and replacement materials for the house.

The net carbon balance of the wood-intensive house indicated a complete offset of the manufacturing emissions by the credit given to the system for forest re-growth – a carbon balance of 2.2 tons CO_2e prior to taking the material to the landfill. The 18-tons CO_2e emitted in the landfill brings the net total to 20.2 tons, significantly lower than the 72 ton total for the typical house. The biomass recovery further improved the wood-intensive house's carbon balance, replacing the methane emitting landfill with net carbon negative energy recovery.

The fossil fuel balance showed a similarly advantageous result for the wood-intensive house as the fuel consumption was reduced 55% in the landfill scenario and 94% when the wood materials are recovered as fuel.

4. Discussion

4.1. Allocation of forest carbon uptake

The model we developed assumed a combination of allocation methods that penalizes the wood products with the entire manufacturing burden while only giving carbon sequestration credit for the materials present in the product itself, ignoring the carbon present in the co-product and waste residue. In other words, while the greenhouse gas emissions were allocated on an economic basis (manufacturing emissions were assigned exclusively to the product), the carbon uptake and generation of fuel in the forest through carbon sequestration and solar capture were allocated on a mass basis. Since all of the wood products came from systems with less than 50% wood utilization, the co-products of production, which are of little economic value compared to the primary product, received more credit for the positive effects of carbon sequestration than the products themselves. We allocated carbon sequestration on a mass basis because the fate of wood co-products is unknown after they leave the system boundaries but consistent economic allocation would assign nearly all of the fuel generation and forest sequestration to the primary product while charging the products that utilize the wood waste with biomass energy consumption, categorized as feedstock in cases that the material is not burned but is used as a material.

The basis for economic allocation of carbon sequestration is a result of the realization that carbon removal from the atmosphere

Table 4
Atmospheric carbon balance and fossil fuel use by the systems considered and their net totals.

	CO_2e (tons)		Fuel (GJ)	
	Typical	Wood	Typical	Wood
Forest				
Forest materials for initial build	(18.3)	(32.5)		
Forest materials for service life	0	(21.8)		
Forest balance	(18.3)	(54.3)		
Manufacturing				
Initial build	60.8	43.6	968.0	536.8
Service life	23.4	12.9	648.6	248.6
Manufacturing balance	84.2	56.5	1616.6	785.4
Landfill with capture				
Direct emissions	5.1	15.1		
Flare	1.0	2.9		
Burned with recovery	2.3	6.8		
Fossil fuel substituted	(2.3)	(6.8)	(25.9)	(77.1)
Landfill with capture balance	6.1	18.0	(25.9)	(77.1)
Biomass recovery				
Combustion process	18.3	54.3		
Fossil fuel substituted	(20.8)	(61.7)	(235.1)	(698.3)
Biomass recovery balance	(2.5)	(7.4)	(235.1)	(698.3)
Total system				
System with landfill	72.0	20.2	1590.7	708.3
System with biomass recovery	63.4	(5.2)	1381.5	87.1

is not an intrinsic value of wood products but is instead an input to the economically managed forest system that is highly dependent on the revenue gained through downstream product use. The European Union's COST initiative [16] recommend treating carbon sequestration on an economic basis as they recognized the dependence of the generation of wood residues on the life cycle of the primary product; this is of particular significance in the life cycle balance of low-yield wood products such as windows.

To consider the potential of allocating carbon sequestration entirely to the primary product we reconsidered the wood utilization. For example, manufacturing 1 m^3 of lumber and plywood requires extracting approximately 2 m^3 of logs from the forest that come from 4 m^3 of standing biomass [3]. Cedar siding and shingles only have a 35% utilization rate after extraction [19] and thus require 2.8 m^3 of logs and 5.6 m^3 of above-ground biomass. Wood window frames have much lower utilization, 25% of lumber or 12.5% overall [24], and thus require 8 m^3 logs and 16 m^3 of biomass for 1 m^3 of window frame. For the wood-intensive house this means that 3.6 times the post-consumer waste is generated as biomass fuel over the life cycle and 7.2 times the waste if slash and stumps are removed as they were in the example described in Fig. 3 [10].

True economic allocation considers both the revenue gained from the primary product and the lower value co-products. Despite recent increases in market prices of pulp, greater than 90% of carbon uptake would be allocated to the primary product under this scenario. By allocating all of the forest process to the primary product, the wood-intensive house generates 2513 GJ over its life cycle and has the potential to produce 5028 GJ of energy if slash and stumps are removed and used for fuel as well.

4.2. Energy self-sufficiency of wood-intensive house during use

To put the manufacturing and construction effects in perspective, the R2000 house was subjected to an energy simulation in the HOT2000 software. HOT2000 is an operating energy analysis program for residential buildings developed by Natural Resources Canada and freely distributed via the web (www.buildingsgroup.nrcan.gc.ca). The house was assumed to utilize a high efficiency, natural gas fired, forced air furnace and the seasonal use of a 3-ton conventional air conditioner. To heat and cool the house, 1643 m^3 natural gas and 1545 kWh electricity are consumed in the winter months and 1301 kWh electricity to power the air conditioner in the summer. Thus, occupancy of the R2000 house consumes 73.1 GJ fossil fuels annually (9.4 GJ towards electricity and 63.7 GJ towards natural gas). Thus, the 698 GJ generated at the end of life of the wood-intensive house could potentially offset 9.5 years of heating and cooling the house. This is not to say, however, that the system is self-sufficient as wood could not necessarily be used to directly heat the house as natural gas could, but instead the biomass could substitute for natural gas in electricity generation and that this would free up natural gas to be used elsewhere.

However, as was described in the previous section, the economic dependence of forestry on building products indicates that the life cycle of the wood materials generates far more wood fuel than we have given credit for in this analysis. The 2.5-TJ fuel generation based on the economic allocation of forest carbon uptake described in Section 4.1 is the equivalent fuel to heat and cool the R2000 house in Ottawa for 34.2 years while the 5.0 TJ (inclusive of slash and stumps) is enough to power the house for 68.4 years.

Ottawa is one of the most energy demanding cities in North America and the selection of city with a more temperate climate would cause the wood fuel to go much further towards a carbon-neutral house through occupancy. For example, a similar simulation was conducted for the R2000 house but with climate data specific to San Francisco, and it was found that the house consumed 13% of the natural gas, 213 m^3, and 66% of the electricity, 1860 kWh. Despite California's greater reliance on fossil fuels to produce electricity (70% vs. 26%), this example only requires 24.3 GJ of fossil fuel annually (16.1 from electricity and 8.2 from natural gas). Thus, the 698 GJ fuel produced at the end of life is enough fuel to power the San Francisco house for 28.7 years, without allocating any waste to the main product. Economic allocation results in a complete offset of the heating and cooling requirements for this home for its entire 100-year service life and causes enough fuel for 2 whole life cycles if the stumps and slash are removed.

Appendix 1. Landfill equations

Eq. (1): GHG directly emitted:

$$W_{kg}(C)(C_{CO_2})(D)(1-\mathrm{LFG_C})(44/12) + W_{kg}(C)(C_{CH_4})(D)(1-\mathrm{LFG_C})(\mathrm{CH_4GWP}\times 16/12) \quad (1)$$

Eq. (2): GHG emitted from LFG energy recovery:

$$W_{kg}(C)(D)(\mathrm{LFG_C})(\mathrm{LFG_R})(44/12) \quad (2)$$

Eq. (3): GHG emitted from LFG flaring:

$$W_{kg}(C)(D)(\mathrm{LFG_C})(1-\mathrm{LFG_R})(44/12) \quad (3)$$

Eq. (4): Energy offset by LFG recovery:

$$(\mathrm{LFG_{HHV}})\left(W_{kg}\right)(C)\left(D\right)(\mathrm{LFG_C})\left(\mathrm{LFG_R}\right)\left[(44/12)(C_{CO_2}) + (16/12)(C_{CH_4})\right] \quad (4)$$

W_{kg}: wood mass in kg
C: carbon content of wood = 0.5
D: decomposition of wood in landfill = 0.24
C_{CO2}: carbon content of wood converted to CO_2 = 0.55
C_{CH4}: carbon content of wood converted to CH_4 = 0.45
CH_4GWP: global warming potential of methane = 25
LFG_C: landfill gas capture efficiency = 0.75
LFG_R: landfill gas energy recovery efficiency = 0.7
LFG_{HHV}: landfill gas higher heating value = 15.8 MJ/kg

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