Woody Biomass Substitution for Thermal Energy at Softwood Lumber Mills in the US Inland Northwest*

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Abstract

Using life-cycle inventory production data, the net global warming potential (GWP) of a typical inland Northwest softwood lumber mill was evaluated for a variety of fuel types used as boiler inputs and for electricity generation. Results focused on reductions in carbon emissions in terms of GWP relative to natural gas as the fossil alternative. Woody feedstocks included mill residues, forest residuals, and wood pellets. In all fuel-substitution scenarios, increasing the use of biomass for heat generation decreased GWP. Using woody biofuels for electricity production is somewhat less effective in lowering carbon emissions than when used for heat energy. Heat generation at the mill under the current practice of using about half self-generated mill residues and half natural gas resulted in a 35 percent reduction in GWP over 100 percent natural gas. The greatest reduction in GWP (66%) was from increased use of forest residuals for heat energy, eliminating the use of fossil fuels as a direct heating fuel at the mill. We summarize the results by documenting that greater use of woody biomass for heat energy will reduce carbon emissions over fossil-based fuels.

Recent technological advances have provided numerous options for the conversion of biomass to energy. These technologies include electricity production, pellet production for residential and industrial heating, woody and agricultural residue to liquid fuels, and steam generation for industrial heating or manufacturing operations. The scientific community has conflicting opinions on the use of biomass for energy, however, both for economic reasons and, more commonly, because of the environment impacts. The challenge is to use wood resources sustainably while improving our economy, yet without adversely affecting our environment. Increasing the use of wood waste as an energy fuel can reduce our need for imported fossil fuels, resulting in many benefits to the economy while at the same time reducing net carbon emissions. Unfortunately, the balancing acts between economics and environmental improvements have been problematic. On one hand, federal agencies are setting greenhouse gas (GHG) reduction standards for acceptable substitutes for fossil fuels. The US Environmental Protection Agency (US EPA) under the 2007 Energy Independence and Security Act (EISA) has set the threshold for cellulosic fuels at a minimum of 60 percent reduction in fossil emissions (EISA 2007, Sissine 2007). However, many critics are claiming that the use of woody biomass for energy actually releases more carbon into the atmosphere because of management, harvesting, and conversion (Schulze et al. 2012). Some argue that biofuels from woody resources are not carbon neutral because of decreases in the forest stand inventory, which reduces carbon sinks, together with the use of fossil fuels for stand management and harvesting, which emit carbon back to the atmosphere (Heiken 2007, Schulze et al. 2012).

Life-cycle assessment (LCA) is a holistic approach to quantify environmental impacts for every stage of production and use of a product, i.e., from cradle to grave. Comparing the environmental benefits of biofuels requires

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* This article is part of a series of nine articles addressing many of the environmental performance and life-cycle issues related to the use of wood as a feedstock for bioenergy. The research reported in these articles was coordinated by the Consortium for Research on Renewable Industrial Materials (CORRIM; http://www.corrim.org). All nine articles are published in this issue of the *Forest Products Journal* (Vol. 62, No. 4).

Forest Prod. J. 62(4):273–279.

measurements across the total life cycle, from forest/biomass growth through combustion (Lippke et al. 2011). Depending on the fuel combusted, carbon is emitted to the atmosphere as ''biogenic CO_2'' or ''fossil CO_2.'' Carbon dioxide is also sequestered, absorbed from the atmosphere by living trees during photosynthesis, and extended to carbon stored in biomass. When biogenic CO_2 is released during combustion, it is considered equal to the amount of CO_2 absorbed during tree growth. Under sustainable forest management, the harvest does not exceed the growth in the forest. Therefore, carbon emissions from the combustion of woody biomass are considered carbon neutral (US EPA 2006, Beauchemin and Tampier 2008, Fernholz et al. 2009). When biofuels replace fossil fuel, the net impact over the long term is a sustainable reduction in CO_2 levels in the atmosphere, some well above the 60 percent threshold reduction in carbon emissions set by the EPA (EISA 2007, Sissine 2007). With the increasing interest in biofuels, it is important to understand the relative impacts of different biofuel uses on carbon. With softwood lumber manufacturers in the US Inland Northwest (INW) as an example (Puettmann et al. 2010b), the objective of this study was to evaluate the different impacts on net carbon emissions from the use of mill residues, wood pellets, and forest residuals as substitutes for natural gas for either heat production for drying or the generation of electricity. Cogeneration for the woody feedstocks was not part of this assessment because the mills in the INW region did not have these operations. We wanted to show the carbon impacts of using waste residues for energy in the mills to offset fossil fuels and to address the issue of collection options for forest residuals for direct heat energy or for electricity. The process models assessed used mill generated wood waste for either direct heat generation or electricity, not both.

In the western United States, wood is an important part of the economy. Western softwood lumber production uses self-generated mill residues for about half of the energy required for drying, with the remainder from natural gas (Milota et al. 2005, Puettmann et al. 2010a). Previous LCA studies have shown that wood drying is the dominant use of energy in the production of lumber, regardless of the geographical region in which the lumber is produced (Milota et al. 2005, Bergmann and Bowe 2010, Puettmann et al. 2010b). Cradle-to-gate impact assessments for softwood lumber consistently show that manufacturing energy is the dominant energy life-cycle stage, consuming 89 to 92 percent of the total energy (Puettmann et al. 2010a). With nearly half of the fuel coming from natural gas, significant carbon emission reductions are possible by converting softwood lumber mills to all woody biomass energy, at least for drying. This article will focus on the impacts on net global warming potential (GWP) of softwood lumber production from cradle to gate, using fuel substitution as boiler inputs for steam and electricity generation alternatives.

GWP is an indicator, expressed as a factor of CO_2, that reflects the relative effect of a GHG in terms of climate change over a fixed time period, commonly 20, 100, or 500 years. For example, the 20-year GWP with substitution for electricity at the mill of methane is 56, which means if the same weights of methane and carbon dioxide were introduced into the atmosphere, methane will trap 56 times more heat than will the carbon dioxide over the next 20 years. Values were converted to kilograms of carbon dioxide equivalents (kg CO_2 eq). GWP compares the amount of heat trapped by a certain mass of the gas in question with the amount of heat trapped by a similar mass of carbon dioxide.

Questions remain on whether it might be better to raise the share of biofuel in solid wood processing facilities to displace the emissions from natural gas or possibly even lower the biomass share. For example, collecting more forest residuals as a part of the harvest for boiler inputs has the potential to provide as much as four times the energy needed for processing energy, resulting in better than self-sufficiency in solid wood production mills (Lippke et al. 2011). Although the cost of collecting forest residuals has been the primary deterrent to their use as biofuel feedstocks, this may not be an obstacle if the value of carbon is increased through incentives to reduce carbon emissions or if the cost of fossil fuels or their emissions increases. When forest residuals are densified at the landing, hauling costs are reduced, potentially making residuals more competitive in serving energy needs, especially where hauling distances have been the primary obstacle to their use (Johnson et al. 2012).

Common forest practices in the West for forest residuals have been to collect the debris into ''slash piles'' and burn them on site or leave the piles to decompose. Lee et al. (2010) reported that in the Pacific Northwest, one-third of a ton of woody biomass residuals is generated for every ton of merchantable logs harvested; however, there is substantial variation in the amount, depending on the source of the biomass. Oneil and Lippke (2009) found that residuals for eastern Washington were almost equal to the volume of merchantable logs, but only about 24 percent of the total standing volume was likely to be recoverable. In either case, if made accessible and affordable, this material could provide a significant source of energy.

Alternatively, it might be better, both economically and environmentally, to increase the use of natural gas in lumber mills and use the forest residuals for electricity production or to bypass the mill completely and convert the residuals to liquid fuels. The conversion of biomass to electricity could offset the wood processing use of fossil fuels by reducing the fossil emissions generated for electricity production. Because of the variety of fuel sources used for electricity production, air emissions vary substantially across the country and are heavily influenced by the availability of alternative energy sources, such as hydropower. These consequences should be noted when considering different fuels for electricity production. The development of large-scale biomass-to-electricity utilities could be limited based on the cost of collection, sustainable feedstock resources, and environmental impacts. Small electric utilities or on-site electricity generation, such as cogeneration at wood product mills, could provide the production of electricity from non–fossil fuel sources, resulting in reductions in GHG emissions. Although cogeneration is not prevalent in INW softwood lumber mills, several US sawmills do generate some of their own electricity (Bergman and Bowe 2010), which does offset the use of electricity from the grid. Bergman and Bowe reported that, on average, 18 percent of the total wood waste used in the mills went to cogeneration. In the northeastern United States, where coal is the primary fuel for electricity generation (63% share), using mill residues for electricity generation could significantly reduce carbon emissions.

Methods

With a previously published life-cycle inventory (LCI) on the manufacture of softwood lumber produced in the INW (Puettmann et al. 2010b), fuel feedstock alternatives such as boiler inputs were compared using GWP as the performance metric. Energy requirements collected from INW softwood lumber manufacturers had an average fuel mix of 54 percent self-generated wood fuel and 46 percent natural gas used as boiler inputs for drying lumber. With the LCI data for softwood lumber production, alternative fuels were substituted as boiler inputs for determining the impact on GWP. All alternatives were modeled using the SimaPro (PRé Consultants 2012) LCA software package. We assessed the GWP (expressed in kg CO_2 eq) of the GHG emissions released by each feedstock alternative (mill residues, natural gas, forest residuals, pellets).

System boundaries

The system boundary encompassed the product manufacturing processes, including material (logs), electricity, and fuels required to produce one cubic meter of finished product (Fig. 1). The cumulative system boundary (cradle to gate) included all upstream flows of energy, fuel, and raw material production (Puettmann et al. 2010a). Fuel combustion emissions and sawmill manufacturing emissions (including dryer and boiler) were included. Log input to sawmills contained both wood and the accompanying bark. Detailed descriptions of feedstock system boundaries can be found in Puettmann et al. (2010b) for softwood lumber, Johnson et al. (2012) for forest residues, and Katers et al. (2012) for pellet production.

Fuel substitutions at the boiler included the mass allocation of the fuel from producing pellets and forest residues. In the current case, where self-generated wood fuels (mill residues) were used, the allocation of the fuel wood portion was on a mass basis at the process center in which the fuel wood was produced, with 100 percent of the fuel wood allocated to the production of rough dry lumber (prior to planning). For a complete description of the softwood lumber production, including boiler operations, see Puettmann et al. (2010b).

The reference for the boiler substitution feedstocks was that a unit consisted of 1 m^3 of finished planed dried softwood lumber. The conversion factor for 1,000 board feet (MBF) was equal to 1.622 m^3.

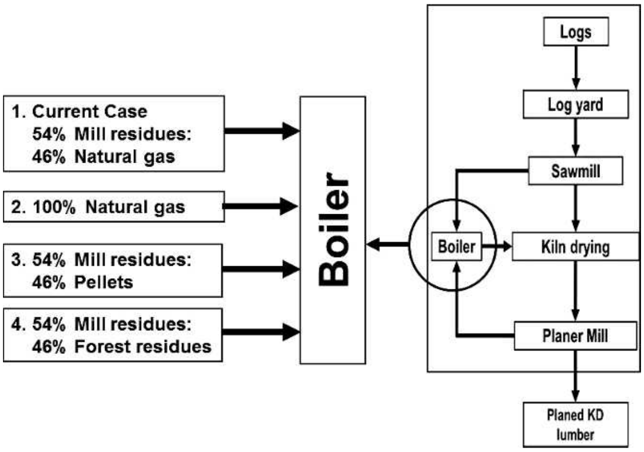

Figure 1.—System boundary for softwood lumber production with boiler substitution scenarios. KD = kiln dried.

Background of data source

INW softwood lumber production.—Softwood lumber is typically dried to a moisture content of 15 percent. Puettmann et al. (2010b) reported approximately 50 percent of the bark generated during debarking, as well as other wood waste sources from downstream processes, were used as wood fuel in the boiler for steam generation. The total wood fuel burned was 110 kg/m^3 at 50 percent moisture content on a wet basis or 55 kg/m^3 of ovendry weight wood fuel. Ovendry wood fuel has an energy content of 20.9 MJ/kg. Wood fuel (55 kg) and natural gas (25 m^3) were the fuel sources consumed in the boiler, meeting 54 and 46 percent of the energy needed, respectively. The INW resource-management scenarios included state or private and national forest ownership for softwood logs. The LCI used an average management and harvest volume scenario that represented 9, 30, and 61 percent from national forest (50:50, gentle:steep slopes), state or private dry sites (90:10, gentle:steep slopes), and state or private moist sites (70:30, gentle:steep slopes), respectively (Oneil and Lippke 2009). Forest-management practices included in the harvesting life-cycle stage were regeneration, seedling growth, thinning (precommercial and commercial), and final harvest, as well as associated equipment use. The system boundary for softwood lumber production included forest management and harvesting, lumber production, and transportation to the mill. LCI data for natural gas were obtained from the US LCI database (National Renewable Energy Laboratory [NREL] 2012). Emissions from the combustion of natural gas were based on AP-42 (US EPA 1998). The natural gas data included extraction, production, combustion, and transportation. Natural gas has an energy content of 38.08 MJ/m^3. The total heat energy requirement for INW softwood lumber was 2,124 MJ/m^3.

Pellet production.—Wood pellet LCI data were obtained from Katers et al. (2012). The system boundary included extraction or feedstock collection, pellet production, combustion of wood pellet fuel, and transportation of feedstocks to pellet manufacturing. Data were based on surveys of Wisconsin wood pellet mills. Wood pellet feedstock included whole log collection and wet and dry mill residues. The energy content of wood pellets was 19.1 MJ/kg.

Forest residues.—Forest residues were collected after conventional logging operations in the INW (Johnson et al. 2012). The average forest type was moist-cold forest with gentle slopes on state or private land. Total residue generated through the primary harvesting activity was 72.1 tonnes/hectare (t/ha; tonnes = metric tons). The primary harvest involved delivery of whole trees to the landing, so the resulting residues were piled at that location. Residue recovery involved grinding at the landing and transportation. A transportation distance of 80.5 km (50 mi) was used from the landing to a feedstock use point. Total residue recovered was 32.5 t/ha (14.48 bone dry tons [BDT] per acre).

Boiler substitution scenarios

Four feedstock alternatives for producing thermal energy at the mill were modeled to assess their impact on GWP. Each alternative was evaluated in a separate scenario.

Puettmann et al. (2010b) reported that the average INW boiler feedstocks used 54 percent mill residues and 46 percent natural gas. This average mix of fuels (labeled the current case) was used in Scenario 1 as the source of thermal energy required to dry the softwood lumber. The second scenario increased the natural gas use to 100 percent of the energy requirements. This scenario rerouted the flow of coproducts produced at the mill from going to the boiler (sawdust, bark, shavings) to a sold coproduct (Fig. 1). The third scenario considered wood pellets as a substitution for natural gas, resulting in 46 percent wood pellets and 54 percent mill residues. The fourth scenario was also a 100 percent biomass-fueled boiler that substituted forest residuals for the natural gas, resulting in a fuel mix of 54 percent mill residues and 46 percent forest residues.

Electricity generation substitution

Electricity is consumed throughout the lumber manufacturing process to run fans, hydraulic conveyors, saws, planers, and sorters. All four scenarios consume electricity for the production of lumber from an average (2008) western electricity grid production system (US LCI 2012; Fig. 2). Puettmann et al. (2010b) reported that the average INW softwood lumber mill consumed 76.23 kWh/m^3 of electricity from the western grid production system. In this region, electricity generation primarily comes from coal, hydropower, and natural gas at 35, 30, and 25 percent, respectively (NREL 2012).

To evaluate the best use for woody biomass as a fuel for INW mills, two additional scenarios were modeled to evaluate the environmental tradeoffs of using woody biomass for heat generation, as in the mill boiler, or as a feedstock for electricity generation. The fifth scenario used the current case (54% mill residues; 46% natural gas) for heat generation and forest residues transported to the mill for electricity generation (Fig. 2). The sixth scenario assumed that all the mill residues generated on site were used for electricity generation to reduce emissions, thus requiring all the heat needed for drying lumber to be produced from natural gas.

Data for the electricity production from biomass were obtained from the US LCI database (US LCI 2012). For Scenarios 5 and 6, the electricity generation was modeled as a process of biomass gasification followed by a gas turbine. The process for electricity generation from wood waste was not assumed to be a process used at sawmills, but more of an average US electricity generation process. The LCI data included the extraction of fuels and raw materials through the production of electricity. Process and fuel emissions were reported together in the original data source and could not be separated.

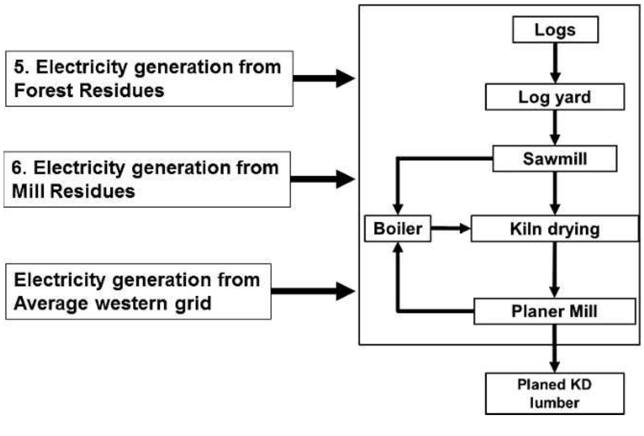

Figure 2.—System boundary for softwood lumber production with electricity generation substitutions. KD = kiln dried.

GWP impact assessment

The LCA results include both an LCI and a life-cycle impact assessment (LCIA). The data include cradle-to-gate environmental impacts from energy and raw materials use, transport, lumber production, and combustion of fuels and feedstocks. SimaPro (PRé Consultants 2012) was used to develop the individual processes. GWP was determined using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2 v.3.0; Bare et al. 2003). TRACI is a midpoint-oriented LCIA methodology developed by the US EPA specifically for the United States using input parameters consistent with US locations, and it uses a 100-year time frame. All calculations in this report for CO_2 absorption are based on 52 percent carbon content for the woody feedstocks (Puettmann et al. 2010b).

Results

Results for all boiler substitution scenarios are references to 1 m^3 of planed dried softwood lumber produced in the INW. Scenario 1 resulted in a GWP of 124 kg CO_2 eq fossil carbon emissions (Fig. 3; Table 1). When the substitution was made to use 100 percent natural gas (Scenario 2), GWP increased 67 kg of fossil carbon emission (+54%) more than the current case. Switching fuel input to wood pellets to displace the natural gas fuel (Scenario 3) decreased fossil emissions by 41 kg CO_2 eq (–33%). Finally, substituting forest residuals for natural gas (Scenario 4) decreased GWP emissions by 58 kg, a reduction in kilograms of carbon dioxide equivalents of 47 percent over the current case.

The usual alternative to using these forest residuals is to eliminate them by open burning or pile burning, where emissions are not controlled and the heat energy cannot be captured. This practice makes the use of forest residuals collection as an energy feedstock particularly attractive. Pellets were less efficient in reducing emissions because of the additional energy (primarily fossil fuel–based) needed to produce pellets; however, hauling costs may be lower for pellets than for collecting forest residuals, making pellets more cost competitive in some situations.

The fuel alternatives analysis showed that biofuels are effective in reducing GWP when substituted for fossil fuels, which is one of the primary objectives in using them (Fig. 3). Lee et al. (2010) reported that the use of forest residuals for energy over on-site slash burning or decomposition reduced GWP emissions by at least 20 percent. The reduction in GHG emissions associated with GWP when biofuels displace fossil fuels depends on the energy content of the biofuel and the quantity of the fossil emissions displaced (Lee et al. 2010). The higher the energy content of the biofuel used, the greater the reduction in fossil emissions and GWP. GWP from gathering, chipping, and hauling forest residuals made up less than 3 percent of the total cradle-to-gate GWP for the combustion of forest residuals. Lee et al. reported similar findings of less than 4 percent for the processing of forest residuals.

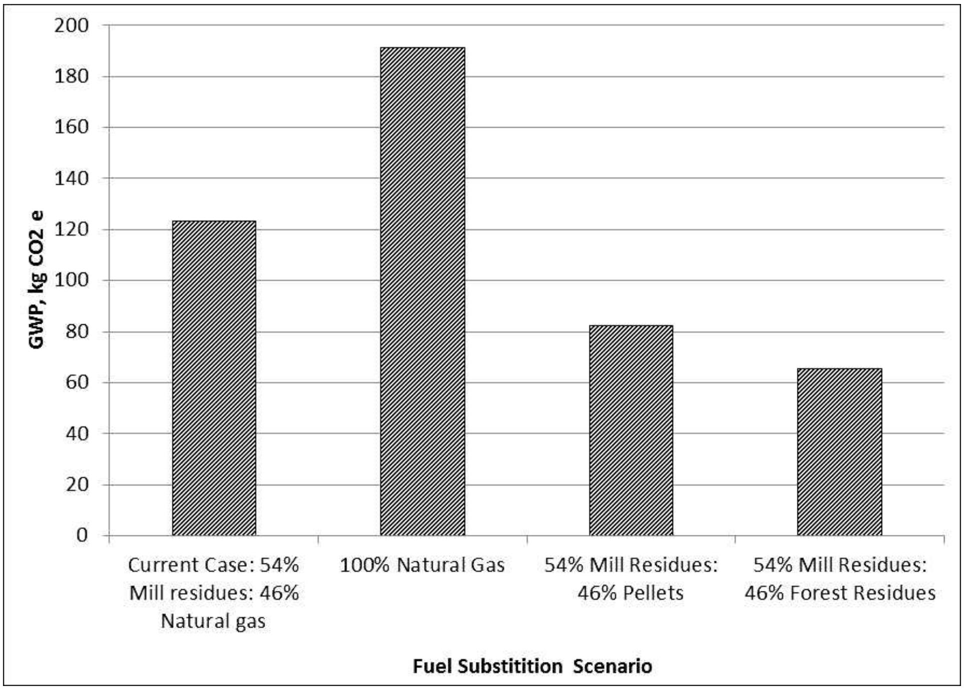

Figure 3.—Global warming potential (GWP) emissions from fossil fuels only, expressed in kilograms of carbon dioxide equivalents when producing 1 m^3 Inland Northwest kiln-dried lumber under different boiler fuel scenarios.

Table 1.—Total and net global warming potential (GWP) in kilograms of carbon dioxide equivalents generated by biomass and fossil fuels combustion in boilers using different fuel sources.[a]

Scenario	GWP (kg CO_2 eq) Biomass	GWP (kg CO_2 eq) Fossil	Absorption (kg CO_2)	Net GWP (kg CO_2 eq)
1. Current case, 54% mill residues:46% natural gas	94	124	−975	−757
2. 100% natural gas	1	191	−869	−677
3. 54% mill residues:46% pellets	223	84	−1,010	−703
4. 54% mill residues:46% forest residues	179	66	−1,064	−819

[a] Boiler fuel input substitution per cubic meter of softwood kiln-dried, planed lumber.

If sustainably managed, biomass feedstocks remove from the atmosphere a quantity of CO_2 approximately equivalent to that released when the biomass is converted to fuel and burned for energy (US EPA 2006, Beauchemin and Tampier 2008, Fernholz et al. 2009). Hence, under sustainable management there is no additional carbon released into the environment when biomass is burned for heat or fuel production. The bioenergy produced more than offsets the fossil energy used, indicating more carbon is absorbed than released.

When biofuels are incorporated into a production process, there are many other processes that can contribute to carbon releases over the products' life cycle, such as the transportation of resources and raw materials, the production of electricity, and the production of other materials. The overall net kilograms of carbon dioxide equivalent emissions reported considers all emissions from all upstream processes (fossil and biogenic) and the carbon absorption prior to harvesting for the production of softwood lumber based on a mass basis of wood removed.

All carbon emissions, both biogenic and fossil based, released through each scenario are shown in Table 1. The total net GWP emission was highest for the pellet substitution (Scenario 3) as a result of the additional energy requirement for their production. The total GWP was lowest for the 100 percent natural gas boiler fuel (Scenario 2), but this scenario produced the greatest amount of fossil fuel–based emissions. When using the EPA metric of reduced fossil carbon emissions as the objective, the current case (Scenario 1) resulted in 35 percent fewer emissions, the pellets case 56 percent fewer, and the forest residues case 66 percent fewer (Table 2).

When CO_2 absorption from and release to the atmosphere during tree growth are properly recognized as inputs and outputs, the net GWP is negative for all fuel-substitution scenarios, signifying that more CO_2 (both biogenic and fossil based) is removed than is released during the production of softwood lumber from cradle to gate (Table 1; Fig. 4). Because the values in Table 1 are referenced to a volume of lumber produced, CO_2 absorption not only includes the biofuel component, it also includes the mass of carbon represented in the 1 m^3 of lumber.

The 100 percent natural gas fuel-input scenario used the least amount of wood, evidenced by the lowest CO_2 absorption: 869 kg CO_2 (Fig. 4). Even this scenario produced a negative net GWP because of the large influence of the carbon stored in the wood product, in terms of carbon mitigation. Net GWP was improved further when the use of

Table 2.—Ratios of carbon displaced to biogenic carbon released and total percent reduction in global warming potential emissions when biomass fuels displace fossil fuels in different boiler fuel scenarios in a softwood sawmill using two electricity generation scenarios.[a]

Scenario	C_{net}/C_{wood}	Emission reduction (%)
Western electricity grid use at the mill		
1. Base case: 54% mill residues:46% natural gas vs. 100% natural gas	0.72	35
3. 54% mill residues:46% pellets vs. 100% natural gas	0.48	56
4. 54% mill residues:46% forest residues vs. 100% natural gas	0.70	66
With substitution for electricity at the mill		
5. Heat generation from 54% mill residues:46% natural gas and electricity generation from forest residues vs. heat generation from 100% natural gas with grid electricity generation	0.68	52
6. Heat generation from 100% natural gas and electricity generation from mill residues vs. heat generation from 100% natural gas with grid electricity generation	0.63	17

[a] All scenarios use 100 percent natural gas for the comparisons.

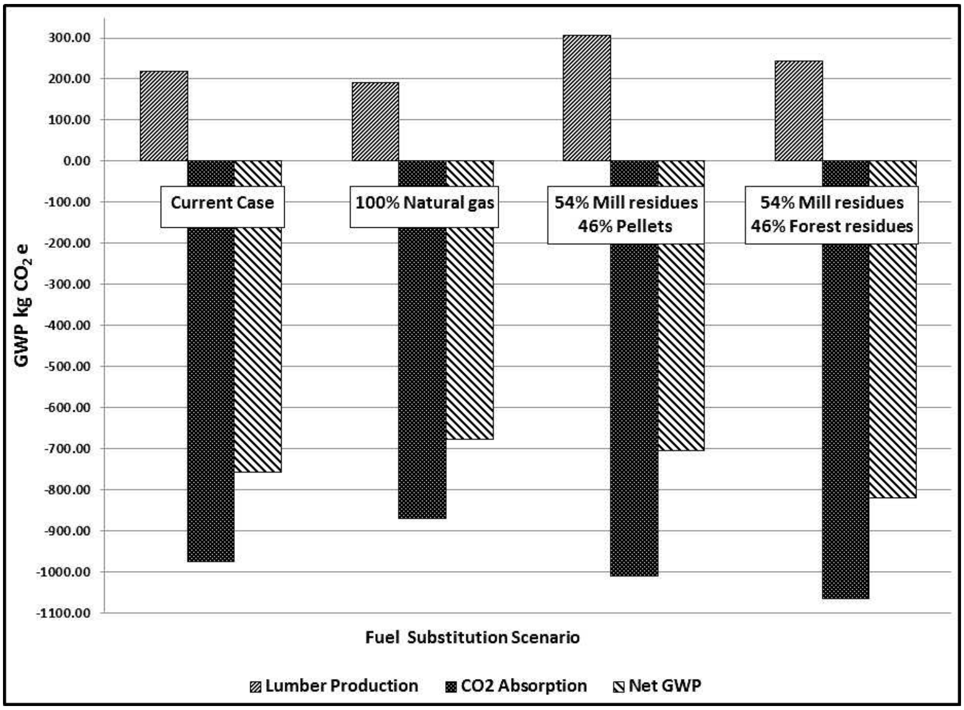

Figure 4.—Net global warming potential (GWP) emissions (biomass and fossil fuel based) expressed in kilograms of carbon dioxide equivalents when producing 1 m^3 Inland Northwest kiln-dried lumber under different boiler fuel scenarios.

wood fuel was increased. Using forest residues for heat generation in the mill and reducing the use of natural gas produced the greatest benefit to net GWP over all scenarios, followed by the current case, and then pellets. Pellets produced the lowest emission reduction over the other biomass fuel scenarios because the feedstocks collected for pellets used so much fossil fuel. Pellets made from waste residuals that do not require as much fossil fuel would perform similarly to and perhaps better than forest residuals. Even when additional energy was required to produce the fuel, in the case of pellets, and carbon emissions were higher, this fuel still showed a reduction in net GWP from the carbon stored in products. As expected, using all natural gas for heat generation for lumber production produced the lowest benefit in net GWP because there was no absorption by biofuel to offset fossil fuel use.

Comparing the net carbon savings over fossil fuels for different biofuels provides insight into best options for wood producers. When boiler inputs came from self-generated mill residues (54%), they embodied 94 kg CO_2 in the feedstock. This resulted in a 0.72-kg decline in fossil emissions for every 1 kg CO_2 in the wood (Table 2). Similar comparison showed that the production of ethanol to displace gasoline by gasification or fermentation resulted in only about a 0.38 reduction in fossil emissions for every 1 kg CO_2 in the wood (carbon net:carbon in wood; Lippke et al. 2012) or only about half the displacement efficiency gained from the mill residuals in a solid wood mill. From a pure efficiency measure of emission reduction per unit of wood produced, using woody biomass in the mill is substantially better than leaving it in the forest to decompose, burning it on site, or even using it to produce transportation fuel. The greatest emission reduction in our scenarios occurred when forest residuals were used for heat generation in the mill, which resulted in a 66 percent emission reduction over the 100 percent natural gas boiler

(Table 2). However, when biofuels are used to produce transportation fuels, even though the efficiency of reducing carbon emission per unit of wood used is low, it more directly contributes to reducing oil imports and the goal of energy independence. Energy independence contributes to the domestic economy and may be judged more important than reducing carbon emissions.

Table 2 summarizes the comparable efficiency metrics for the mill and the carbon tradeoffs for using biofuels for heat generation versus electricity generation. Neither electricity scenario (forest residues or mill residues) reduced emissions better than directly using forest residuals for heat generation. The results did show that using mill residuals for electricity production instead of for heat in the mill reduced carbon emissions by 17 percent compared with 35 percent. All scenarios showed that using the least amount of fossil fuels at the mill reduced net carbon emissions.

Conclusions

The greater use of woody biomass for heat energy reduced carbon emissions compared with fossil-based fuels. In all fuel-substitution scenarios, increasing the use of biomass for heat generation decreased GWP. Using woody biofuel for electricity production was somewhat less effective in lowering carbon emissions than when it was used for heat energy. But further investigation into forest residual collection methods, transportation distance, feedstock type, and moisture content, to name a few, could influence the biofuel impact. Heat generation at the mill under the current case of using about half self-generated mill residues and half natural gas resulted in a 35 percent reduction in GWP over heat production compared with using 100 percent natural gas. The greatest reduction in GWP compared with 100 percent natural gas (65%) resulted when forest residues were collected, chipped, and hauled to the mill for heat energy, eliminating the use of fossil fuel for drying.

Controversy exists over exactly how long wood (lumber) remains in service and the fate of wood after demolitions. Such controversies become more pronounced when the final disposal is landfilling and when heat recovery from the landfill is included. Although these fates of wood will have an additional impact on GWP, the level of this impact—whether positive or negative—remains uncertain, is outside the scope of this study, and does not alter the conclusions for the cradle-to-gate analysis. Further investigation into factors such as forest residual collection methods, transportation distance, feedstock type, and moisture content, to name a few, could help to better assess the impact of biofuels on carbon emissions.

Literature Cited

Bare, J. C., G. A. Norris, D. W. Pennington, and T. McKone. 2003. TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. *J. Ind. Ecol*. 6(3–4):49–78.

Beauchemin, P. A. and M. Tampier. 2008. Emission from wood-fired combustion equipment. http://www.env.gov.bc.ca/epd/industrial/pulp_paper_lumber/pdf/emissions_report_08.pdf. Accessed September 5, 2012.

Bergman, R. D. and S. Bowe. 2010. Life-cycle inventory of softwood lumber manufacturing in the northeastern and north central United States. CORRIM Phase II Final Report: Module D. February 2009. 50 pp. http://www.corrim.org/pubs/reports/2010/phase2/Module_D.pdf. Accessed September 5, 2012.

Energy Independence and Security Act (EISA). 2007. Energy Independence and Security Act of 2007. December 19, 2007. 311 pp. http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf. Accessed September 5, 2012.

Fernholz, K., S. Bratkovich, J. Bowyer, and A. Lindburg. 2009. Energy from wood biomass: A review of harvesting guidelines and a discussion of related challenges. Dovetail Partners Inc., Minneapolis, Minnesota. July 29, 2009. www.dovetailinc.org/files/DovetailBioGuides0709.pdf. Accessed September 5, 2012.

Heiken, D. 2007. The straight facts on forest, carbon, and global warming. *Oregon Wild,* version 1.4, May 25, 2007. http://tinyurl.com/2by9kt. 25 pp. Accessed September 5, 2012.

Johnson, L., B. Lippke, and E. Oneil. 2012. Modeling biomass collection and woods processing life-cycle analysis. *Forest Prod. J*. 62(4):258–272.

Katers, J. F., A. J. Snippen, and M. E. Puettmann. 2012. Life-cycle inventory of wood pellet manufacturing and utilization in Wisconsin. *Forest Prod. J*. 62(4):289–295.

Lee, C., P. Erickson, M. Lazarus, and G. Smith. 2010. Greenhouse gas and air pollutant emissions of alternatives for wood biomass residues. Final Draft version 2.0, November 2010. Stockholm Environmental Institute. 89 pp.

Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, and R. Sathre. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: Knowns and unknowns. *Carbon Manag*. 2(3):303–333.

Lippke, B., M. E. Puettmann, L. Johnson, R. Gustafson, R. Venditti, P. Steele, J. F. Katers, A. Taylor, T. A. Volk, E. Oneil, K. Skog, E. Budsberg, J. Daystar, and J. Caputo. 2012. Carbon emission reduction impacts from alternative biofuels. *Forest Prod. J*. 62(4):296–304.

Milota, M. R., C. D. West, and I. D. Hartley. 2005. Gate-to-gate life-cycle inventory of softwood lumber production. *Wood Fiber Sci*. 37(CORRIM Special Issue):47–57.

National Renewable Energy Laboratory (NREL). 2012. U.S. life cycle inventory database. http://www.lcacommons.gov/. Accessed August 24, 2012.

Oneil, E. and B. Lippke. 2009. Eastern Washington biomass accessibility. Report to Washington Legislature, School of Forest Resources, College of the Environment, University of Washington. 44 pp.

PRé Consultants. 2012. SimaPro7 life-cycle assessment software package, version 7.3.2. Amersfoort, The Netherlands. http://www.pre-sustainability.com. Accessed September 5, 2012.

Puettmann, M. E., R. Bergman, S. Hubbard, L. Johnson, B. Lippke, E. Oneil, and F. G. Wagner. 2010a. Cradle-to-gate life cycle inventory of US wood products production: CORRIM phase I and phase II products. *Wood Fiber Sci*. 42(CORRIM Special Issue):15–28.

Puettmann, M. E., F. G. Wagner, and L. Johnson. 2010b. Life cycle inventory of softwood lumber from the inland Northwest US. *Wood Fiber Sci*. 42(CORRIM Special Issue):52–66.

Schulze, E.-D., C. Loener, B. E. Law, H. Haberl, and S. Luyssaert. 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*. DOI:10.1111/j.1757-1707.2012.01169.x.

Sissine, F. 2007. Energy Independence and Security Act of 2007: A summary of major provisions. Congressional Research Service (CRS) Report for Congress RL34294. December 2007.

US Environmental Protection Agency (US EPA). 1998. Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors. AP 42. 5th ed. Vol. I. Chap. 1: External combustion sources. Natural gas combustion. US EPA, Washington, D.C. http://www.epa.gov/ttn/chief/ap42/EIIP/POINTSRC/Ii02.pdf. Accessed October 2, 2012.

US Environmental Protection Agency (US EPA). 2006. Emissions Factors & AP-42, Compilation of Air Pollutant Emission Factors. 5th ed. Vol. I. Chap. 1: External combustion sources. Wood residue combustion in boilers. US EPA, Washington, D.C. http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s06.pdf. Accessed September 5, 2012.

US Life Cycle Inventory (US LCI). 2012. Electricity, at grid, WECC, 2008. https://www.lcacommons.gov/nrel/search. Accessed September 5, 2012.