Gate-to-Gate Life-Cycle Inventory on Hardwood Sawmills in the Northeastern Region of the United States

by

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ABSTRACT

Using sustainable building materials is gaining a significant presence in the United States therefore proving sustainability claims are becoming increasingly more important. Certifying wood products as green building materials is vital for the long-term productivity of the wood building industry and for forest management. This study examined hardwood lumber manufacturing using Life-Cycle Inventory methodology. Material flow and energy type and use were identified for hardwood sawmills in the northeastern United States. Energy consumption of 608 MJ of electricity and 5,800 MJ of thermal energy per m^3 were determined for the manufacturing of planed dry hardwood lumber from incoming logs. Burning green wood residues on-site generate the most energy. Hardwood log volume conversion to planed dry lumber of 43.7% was estimated. Modeling data estimated biomass and fossil carbon dioxide production of 428 kg per m^3 and 139 kg per m^3, respectively. Increasing wood fuel use, a carbon-neutral process, would decrease the environmental impact of hardwood lumber manufacturing and increase its value as a green building material.

INTRODUCTION

Hardwood lumber is used primarily in wood flooring, pallets, furniture, cabinets, and moulding. The total annual hardwood production for the United States in 2005 was 10.6 billion board feet (USCB 2006a). Most hardwood lumber is consumed domestically, but there was an estimated 1.35 billion bf exported in 2005 (HMR 2006).Domestic hardwood lumber production occurs mostly in the eastern United States, with an annual production of 10.2 billion board feet[1] (bf) split equally between the northeastern and southeastern states. A small percentage of hardwood lumber production occurs on the West Coast.

Economic costs, energy use, and environmental impact of residential building products are playing an increasing large part due to increase residential building. Two major reasons for the increase in residential building are the increase in average size and the number of U.S. new single-family residential housing units. The average-size single-family residential home has increased from 2,075 square feet in 1991 to 2,434 square feet in 2005 and completed single-family residential units have roughly increased 100% to 1.64 million units during this same period (USCB 2006b).

"Green building" is defined as the practice of improving energy efficiency for materials, construction, and operation while reducing the overall environmental impact of building. Two percent ($7.4 billion) of new residential starts in 2005 were classified as "green buildings", and the minimum market share is expected to increase to five percent ($19

[1] A board foot measures 12 by 12 by 1 inch.

billion) by 2010 (MHC 2006). Developing a sound policy for building practices, especially for green building, must be a priority if the United States is to decrease its environmental burden on the world's resources. However, scientific evidence is needed to evaluate claims for green building materials.

Providing accurate baseline data for hardwood lumber production through a gate-to-gate Life-Cycle Inventory (LCI) are part of sustainable practices regarding building styles, construction materials, product improvements for energy consumption, and carbon sequestration policies. A LCI of hardwood lumber production will provide useful data to help evaluate the environmental importance of hardwood lumber production. In addition, these data can be interconnected into the scientific database managed by the National Renewable Energy Laboratory to complete a Life-Cycle Analysis of hardwood lumber-related wood products (NREL 2007).

Life-Cycle Inventory provides an accounting of the energy and waste associated with the creation of a product through use and disposal. In this study, the gate-to-gate LCI tracks hardwood lumber production from hardwood logs stored in the log yard to planed dry lumber leaving the planing process. Life-Cycle Analysis (LCA) is a broader examination of the environmental and economic effects of a product at every stage of its existence, from harvesting to disposal and beyond. Such a cradle-to-grave assessment is beyond the scope of this study.

Hardwood logs sawn into rough green lumber are typically dried in conventional dry kilns using wood and fossil fuels as heat sources (Denig *et al.* 2000). The sawing process consumes the highest percentage of electrical energy. Prior to drying the lumber, the boards are stickered (separated by thin wood strips) and stacked to aid drying and prevent drying defects. The drying process consumes roughly 70% to 80% of the total energy required for producing hardwood lumber (Comstock 1975). The rough dry lumber is planed to required dimensions when drying is complete.

PROBLEM STATEMENT

Green building awareness is growing with both residential and commercial consumers. As the public, the building industry, and policy makers embrace the green building industry, scientific evidence is required to evaluate claims about building products. It is important for both the consumer and the wood building industry to know the environmental and energy burdens of wood compared to non-wood building practices. This information also has implications for the long-term competitiveness of the forest products industry and welfare of our nation’s forests. Healthy forest management requires a healthy forest industry. It is essential that the data gathered from processing logs into hardwood lumber be available to document exactly what benefits and costs are associated with the decision-making policies for the entire building industry.

The goal of this study was to document the gate-to-gate LCI of planed dry lumber production from hardwood logs. Documentation showed the material flow, energy type and use, and emissions for the hardwood lumber manufacturing process on a per unit volume basis of planed dry lumber for the northeastern United States (Figure 1). Primary mill data were collected through a questionnaire (Appendix A - Page 1-7) mailed to lumber mills, and secondary data were collected from peer-reviewed literature per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2004). Material and energy balances were calculated from primary and secondary data. Using these material and energy data, the environmental impact was estimated by modeling emissions using the software package SimaPro 7 (Pre' Consultants 2007), which follows ISO 14040 protocols. SimaPro has been used in previous CORRIM-initiated Phase I LCI projects (modules): softwood lumber (Milota et al 2005), softwood plywood (Wilson and Sakimoto 2005), I-joist production (Wilson and Dancer 2005), glue-laminated timbers (Puettmann and Wilson 2005), and laminated veneer lumber (Wilson and Dancer 2005). This LCI study is part of the Phase II projects sponsored by CORRIM.

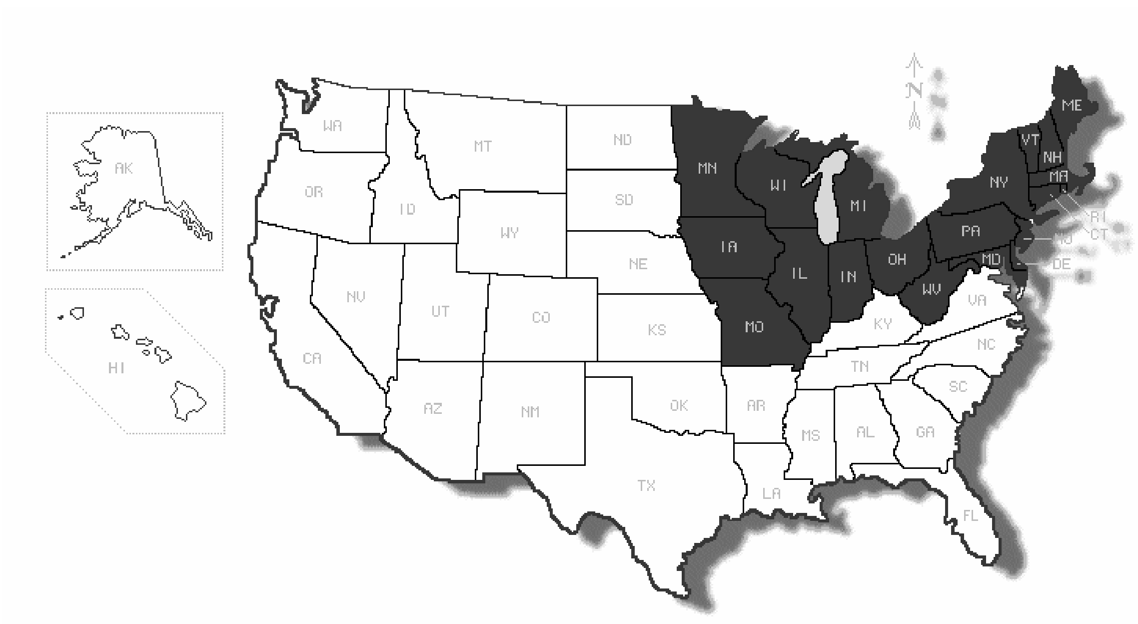

Figure 1. Area selected for Life-Cycle Inventory of hardwood lumber production in the United States.

STUDY OBJECTIVES

Objective 1

Measure the material and energy inputs and outputs for the manufacturing of planed kiln dry hardwood lumber and model the environmental impact through a gate-to-gate Life-Cycle Inventory.

Objective 2

Identify environmental process improvement opportunities for hardwood lumber manufacturers in the northeastern United States by modeling various manufacturing scenarios.

LITERATURE REVIEW

It is important to define several terms used for Life-Cycle research.

Terminology

Life-Cycle Analysis

Life-Cycle Analysis (LCA) uses a rigorous methodology to find the total environmental impact for a particular product referred to as "cradle-to-grave" (raw material extraction to waste disposal) analysis (Figure 2). This analysis includes the environmental and energy costs on a per unit basis using Life-Cycle Inventory (LCI) data from individual LCI studies. These LCI studies are resource extraction, transportation, primary and secondary processing, final product use, maintenance, and final disposal for a particular product (Figure 3). Results from the LCI are used to assess environmental impact (Bowyer *et al* 2005).

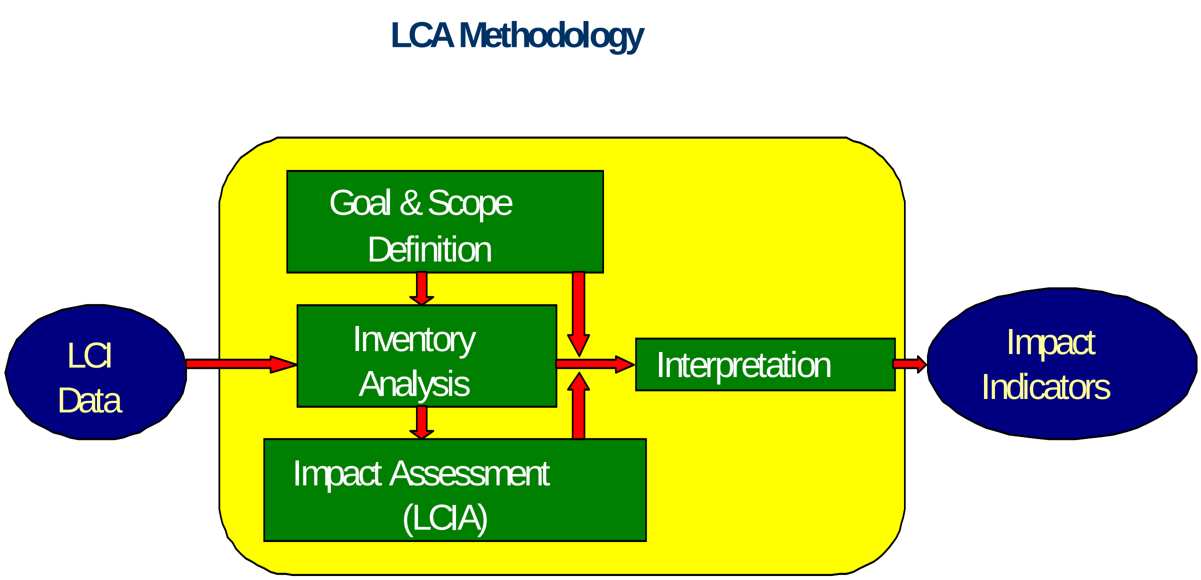

Figure 2. Life-Cycle Analysis Methodology

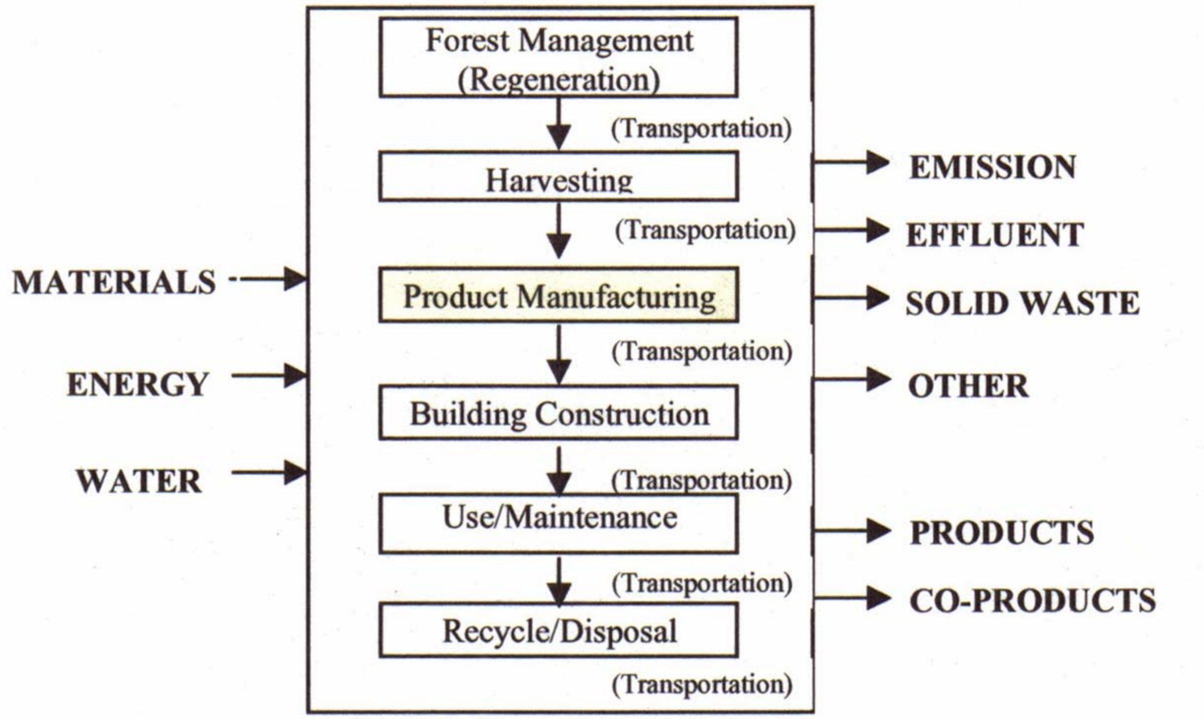

Figure 3. Complete Life-Cycle from regeneration of trees to disposal of wood materials

Life-Cycle Inventory

A Life-Cycle Inventory (LCI) measures all the raw material and energy inputs and outputs to manufacture a particular product on a per unit basis within carefully defined system boundaries. This is often referred to as a gate-to-gate LCI. For this LCI study, hardwood lumber manufacturing falls within the product manufacturing section of the LCA. The material outputs are products, co-products, waste by-products either recycled or landfilled, and emissions to air, water, and soil (Wilson, 2005).

Life-Cycle Impact Assessment

Life-Cycle Impact Assessment (LCIA) uses the gate-to-gate LCI to explore the other aspects of production and use regarding the following four areas: resource depletion and ecosystem, human, and social health (Bowyer, et al. 2005). LCIA gives insights for architects, engineers, and designers on raw materials, product choices, and disposal methods. Learning the LCIA of a particular material allows stakeholders to make informed choices based on science rather than anecdotal evidence. Primary data gathered through industry surveys and secondary data collected from literature were analyzed for its Life-Cycle Impact Assessment (CORRIM 2004).

History and Evolution

When and Why Life-Cycle Research Developed

Learning how our societies affect our environment has interested and driven people for hundreds, perhaps thousands of years (e.g. collapse). Past societies have declined for various reasons, one of which was the lack of available resources or the lack of understanding about availability of these resources (e.g. scarcity). Consumption of natural resources is a fundamental part of past and present societies. As the United States and world populations grow, understanding the environmental impact of the products we manufacture and use is critical for developing sustainable societies. Conducting LCI studies helps us provide the most informed choices for these products. (Benedick 2000).

An early example of Life-Cycle practices involved Coca Cola and its use of glass bottles through a study in 1969 by Harry Teasley, Jr. (Bowyer *et al* 2005). One part of this particular study examined the environmental impact of substituting single-use plastic bottles for refillable glass bottles. Contrary to popular opinion and expectation, the study showed single-use plastic bottles consume less hydrocarbon raw material than did glass bottles (Duda and Shaw 1997).

Consortium for Research on Renewable Industrial Materials (CORRIM)

In 1976, the National Academy of Science formed the Consortium for Research on Renewable Industrial Materials (CORRIM) to examine energy impacts of using renewable materials. CORRIM evaluated the energy issues for building materials and wrote a report that documented wood's energy efficiency (Boyd *et al* 1976).

In 1997, CORRIM was re-formed to update the 1976 study using LCA methods to address environmental issues related to wood products. CORRIM is now made up of 15 wood-related research institutions including the USDA Forest Products Laboratory. CORRIM plans to help develop a database of peer-reviewed information quantifying both economic and environmental impacts of wood and non-wood building materials. Rigorous guidelines were developed by CORRIM for the researchers involved in conducting LCI studies (CORRIM 2004). CORRIM projects started in the Pacific Northwest and the Southeast focusing on glulam, plywood, oriented strand board, softwood lumber, laminated veneer lumber, and trusses. These LCI studies are referred to as Phase I projects.

For Phase I, CORRIM released a study comparing the energy use and environmental load of construction and operation of a wood-framed house to a steel-framed house and a concreteframed house in two different locations (Minneapolis and Atlanta) in the United States. The results mostly favored the wood-framed house in both locations when evaluated on five energy and environmental impact categories (Lippke *et al* 2004). CORRIM's efforts are producing data to help establish environmental standards now being developed.

Phase II projects are now being conducted. These gate-to-gate LCI studies focus mostly on the Inland West and the Northeast, and are intended to extend the present geographic coverage. These projects include hardwood lumber and flooring, softwood lumber, oriented strand board, and other forest resources.

Stakeholder Perspectives on Development

Several major stakeholders who have an interest in the application of LCI data include government agencies, building industries, consultants, and academia. Each stakeholder views the LCI work differently but all have the following concerns when conducting LCI studies: confidentiality, improper assumptions and system boundaries, misuse or misunderstanding by others, and poor data quality. In this study, confidentiality of the mill participants and the data provided by individual mills was stressed during all our discussions. Regardless of any drawbacks, all stakeholders see LCI studies as opportunities. Industry values LCI studies because of the scientific basis used in examining the environmental impacts of products and the potential for process improvement, while government and academia would use the resulting LCA as decision-making tools (de Beafort-Langeveld *et al* 2003).

METHODOLOGY

Basic Steps for Life-Cycle Research

There are four basic steps in Life-Cycle research (Bowyer *et al* 2005):

1. Describe the study goal and the model scope
2. Develop product Life-Cycle model
3. Show the environmental loads based on inputs and outputs of system
4. Select proper product or process based on result-driven choices

These items are essential for providing data quality, data analysis, and data representation needed for LCI studies to withstand rigorous scientific review. These steps were used to guide this research project.

Hardwood Lumber Manufacturing and the Four Main Unit Processes

Production of hardwood lumber starts with hardwood logs that are typically trucked to the sawmill and stored in the log yard until sawn. Logs may be stored wet or dry depending upon species and season. There are four main unit processes in producing hardwood lumber: sawing, drying, energy generation, and planing (Figure 4). In the sawing process, the hardwood logs are sawn into mostly 1-in (25.4 mm) thick rough green lumber of random widths and mostly 8-ft (2.44-m) lengths. The sawing process usually consumes the most electricity of all unit processes. Once the rough green lumber is scaled (to measure production volume) and stickered for drying, the lumber is typically dried to 6-8% moisture content on a dry basis (MC_{DB}) using mostly energy-intensive drying methods (e.g. dry kilns). After drying, the rough dry lumber is planed to the required dimension. The energy generation process provides electricity from the power grid and heat primarily produced on-site for the other three processes.

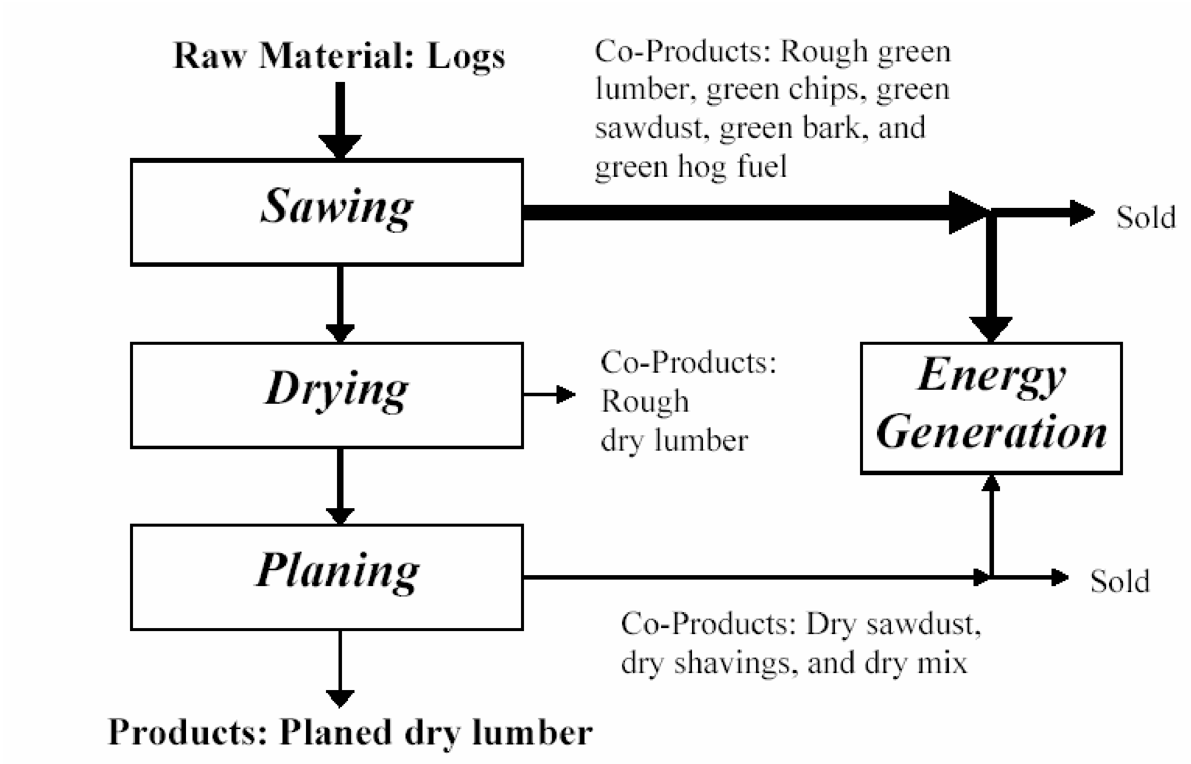

Figure 4. Description of the four unit processes for hardwood lumber manufacturing showing material flow.

Sawing

This unit process begins with logs in the mill yard and ends with sawn rough green lumber and wood residue from the sawing process: bark, sawdust, slabs, edgings, and chips. Any combination of these materials is termed hog fuel. Most wood residue is sold as a co-product, but some residue, especially sawdust, are combusted as fuel.

Drying

This unit process begins with rough green lumber and ends with rough dry lumber bound for the planer mill. Drying produces most of the volatile organic compounds (VOC) generated on-site and uses the most energy produced on-site from wood and fossil fuel combustion. Several different drying methods are employed depending on species and wood residue use.

Energy Generation

This unit process provides all on-site heat and some on-site electricity for the other three processes by burning wood, natural gas, oil, or propane. The outputs of this unit process are steam and hot water from boilers, combustion gases for drying, electricity from cogeneration units, and solid waste (wood ash) and air emissions (e.g. CO_2, CO, and particulate) from combustion.

Planing

This unit process begins with stickered, rough kiln-dried lumber and produces surfaced and packaged lumber, sorted by type, size, and grade. Planing also generates planer shavings, sawdust, and lumber trim ends (dry wood residue). This process is the final stage of manufacturing. Some dry wood residue is combusted on-site in boilers for energy but most is sold as co-products. A particular type of planing is termed skip planing. Some planed lumber is only skip (hit or miss) planed from 25.4 mm (1 in.) to 23.8 mm (0.9375 in.) instead of the standard 20.6 mm (0.8125 in.) for 4/4 hardwood lumber.

Functional Unit

Material flows, energy use, and emission data are standardized to a per unit volume basis for planed dry lumber of 1.0 cubic meter (m^3), i.e., the final product of the hardwood lumber manufacturing process. One cubic meter of planed dry lumber equals 0.568 nominal thousand board feet. The United States industry standard uses nominal dimensions and commodity lumber is sold by variations of a thousand board feet (MBF). In this study, the standard dimensions used to convert board feet to cubic meters are the nominal dimensions of 1 by 6 in. (25.4 by 152 mm) with actual planed dimensions of 0.8125 by 5.5 in. (20.6 by 140 mm) for an 8-ft (2.44-m) board. Rough green lumber and rough dry lumber are assumed to be 1.0625 by 5.6875 in. (27.0 mm by 144 mm) and 1.0 by 5.625 in. (25.4 by 143 mm), respectively, and board length is 8.17 ft (2.49 m) prior to planing (FPL 1999). Allocating all material and energy on a per unit basis of 1.0 m^3 planed dry lumber standardizes the results to meet ISO protocols and can be used in other CORRIM studies including LCA (ISO 1998; ISO 2005; CORRIM 2004).

System Boundaries

Boundary selection is important because the material and energy that cross this boundary need to be accounted for (Figure 5) through the gate-to-gate Life-Cycle Inventory. There are two boundaries as defined by CORRIM (Wilson and Sakimoto 2005) used to track the environmental impact of hardwood lumber production. One is the total (cumulative) system boundary (solid line in Fig. 5) that includes both on-site and off-site emissions for all material and energy consumed. The site system boundary (dotted line in Fig 5) is the environmental impact for emissions developed just at the hardwood sawmill (i.e. on-site) from the four unit processes. Examples of off-site emissions are grid electricity production, transportation of logs and lumber to and from the mill, and fuels produced off-site but used on-site.

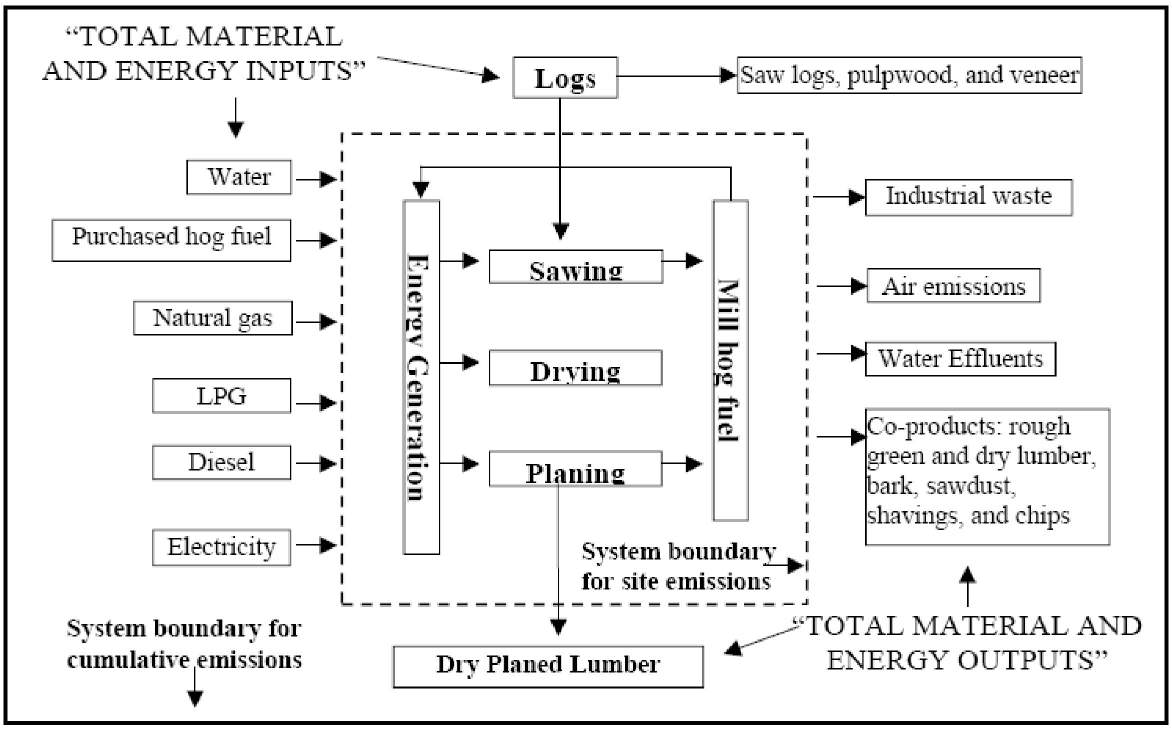

Figure 5. System boundaries for hardwood lumber production

Data Collection

Survey

Data collection was a difficult and time-consuming part of the Life-Cycle Inventory. Developing the questionnaire (Appendix A - Page 1-7) used to collect the necessary primary mill data took a long time. After reviewing the softwood lumber LCI questionnaire from a previous Phase I project and receiving training on SimaPro 6.0 in December of 2004, we developed a shorter, revised questionnaire for the hardwood lumber industry. Jim Wilson, Vice President of CORRIM and Professor Emeritus at Oregon State University, reviewed the questionnaire. Afterward, a Wisconsin hardwood sawmill pre-tested the questionnaire during the spring and summer of 2006. About 18 hours were needed to complete the draft questionnaire by the pre-testing company.

Mill Participants

In the spring of 2005, we contacted Utilization and Marketing personnel of the states with some of the highest hardwood lumber production including Missouri, Wisconsin, and Michigan. In the summer of 2005, we, also, contacted two hardwood lumber manufacturing associations: the Hardwood Manufacturer Association (HMA) and the National Hardwood Lumber Association (NHLA). See Appendix B - 1 for the official letter mailed to Susan Regan, Executive Vice-President of the HMA. An official letter was also sent to Gary Baldwin of NHLA on August 9, 2005. Both associations showed initial interest but we did not have any commitments from either organization for 2005 (a plan to discuss this LCI project with Susan Regan from HMA in mid-September was cancelled).

In the spring of 2006, we again contacted both NHLA and HMA. Another letter was sent to Susan Regan on July 13, 2006 (Appendix B - 2). After several oral and written discussions on this LCI study, Susan Regan invited us to Iowa for the HMA Regional Meeting held October 2006 to discuss the project with the board members of the HMA. HMA is a trade organization comprised of roughly 130 hardwood lumber companies in the eastern United States that process 2.5 billion board feet of 26 hardwood species annually. The HMA board members from the northeastern and southeastern states decided to support the project by having all the board members complete the questionnaire by November 30, 2006. Ms. Regan provided us with the contact information for the board members. Several follow-up calls and emails were completed about 1 month prior to the deadline, around the day of deadline, and about 1 week after the deadline of November 30. Sufficient data from 20 northeastern hardwood lumber mills were received as of January 4, 2007, to exceed the minimum CORRIM protocol requirement to ensure adequate data quality.

Project Assumptions

Four different log scales (Scribner, Scribner Decimal C, Doyle, and International ¼) used by the 20 mills gave log inputs in thousand board feet (MBF). Common U.S. log scales estimate the green lumber output that might be sawn from a log, whereas lumber scales measures the actual green lumber volume produced from the log. Most other countries, including Europe, use a cubic log scale that measures the actual log volume (minus the bark). The accuracy of U.S log scales varies with log diameter, type of sawing method, and sawing efficiencies. Large diameter logs typically produce more lumber for a given log scale volume than do small diameter logs. There is a typical volume difference between the log and lumber scale referred to as either overrun or underrun depending on whether the lumber scale or the log scale is higher. If the lumber scale is higher, there is an overrun. In this study, a 16% overrun was estimated. An average log conversion of 5.35 cubic meters per thousand board feet was used based on an average log diameter of 15 in. reported from a random sample of the participating mills and assuming a mixture of long and short logs (Spelter 2002).

As part of the CORRIM protocol for ensuring data quality, an overall "wood balance" is required to fall within 5% from material input to material output. Log mass was calculated based on the previous assumption of 5.35 cubic meters per thousand board feet and an average green density of 864 kg per m^3. Green lumber weights were developed from the National Hardwood Grading Rules (NHLA 2007). In this study, a 3.0% difference was calculated before and after sawing which fell within the CORRIM requirement.

Higher heating values (HHV) were used to convert volume or mass basis of a fuel to its energy value. Higher heating value (HHV) represents the energy content of a fuel with the combustion products such as water vapor brought to 25ºC (77ºF) while the lower heating value (LHV) ignores the energy produced by the combustion of hydrogen in fuel. HHV is the preferred method used in the United States.

A standard check was done on energy use for drying hardwood lumber. This study considered energy used on-site that included drying lumber but also energy for plant heating, walnut steaming, and electrical cogeneration. These sub-processes are typically not associated with values found in previous studies when calculating energy used in drying. Therefore, the three just stated sub-processes were not included in the following energy checks.

Using the following conditions: initial moisture content on a dry basis (MC_{DB}) of 80%, final MC_{DB} of 7%, boiler efficiency of 66.7%, kiln efficiency of 50%, and 15.2 MJ of energy to remove 1% moisture from 1.0 m^3 rough green lumber (34,561 BTU for 1% moisture per MBF) based on literature values, a total of 3,308 MJ per 1.0 m^3 (7.53 million BTU per MBF) rough green lumber was calculated (Wengert 1980). An estimated value of 3,560 MJ per 1.0 m^3 (7.65 million BTU per MBF) found from actual mill data resulted in a 1.6% difference between the literature and the actual values. Also, 9.82 MJ per kg (4,230 BTU per lb) of water would be removed during the drying process assuming using a moisture loss of 40% on a wet basis.

Energy use for the drying process was determined to be ±152% of the average weighted value for the 18 mills drying lumber. This percentage indicated the large variance found was due significantly to the different ages and types of drying technology and types of species being dried. Average technology was assumed with processes producing similar outputs in North America for modeling the environmental burden.

Primary data were collected through the pre-tested questionnaire in accordance with ISO protocol and CORRIM research guidelines. Missing values were not weight averaged for that particular process per ISO protocol to maintain good data quality. Primary data showed that the major species represented were red oak (27.6%), white oak (8.6%), yellow poplar (20.8%), hard maple (16.3%), soft maple (4.7%), and black cherry (5.0%) of total sawn wood. The US Census Bureau 2005 data showed the following percentages (ignoring the categories of not specified by kind and mixed ungraded hardwoods) of 35.2%, 16.8%, 14.4%, 7.0%, 5.2%, and 3.7%, respectively, for the northeastern region.

Green and dry wood density and specific gravity values found in the Wood Handbook (1999) for the 10 major wood species were used to determine the mass basis conversion from board feet. A weighted density of 854 kg/m^3 (53.3 lb/ft^3) and 624 kg/m^3 (38.9 lb/ft^3) was used for green and kiln dry lumber, respectively.

Volatile organic gas emissions were found through a secondary data source (Rice and Erich 2006) because primary data were not provided by the mill questionnaires.

All bark produced was assumed to be sold off-site as mulch. Bark was not given an allocation for an environmental burden in SimaPro per CORRIM research guidelines (CORRIM. 2004). Allocation refers to the distribution of environmental burden.

The LCI study covered one full year during the years 2005 and 2006 depending when an operational (fiscal) year started at each hardwood lumber company and the geographical area covered the northeastern United States shown in Figure 1.

Modeling Software Selection

Modeling software was needed to generate LCI air, water, and land emission data from the weight averaged results of material flow and energy use and type for hardwood lumber manufacturing in a systematic and transparent way. Also, the software would follow the ISO 14040 protocols related to environmental managements when the LCI practitioner followed the basic four steps of life-cycle research. SimaPro was the modeling software selected and SimaPro training was completed in December 2004.

SimaPro 7 follows the ISO 14040 standards for environmental management and documentation. Other software programs for Life-Cycle Analysis were considered but SimaPro has been the preferred software by CORRIM and was used in Phase I of the other Life-Cycle Inventory projects sponsored by CORRIM. Phase I projects dealt mostly with forest resources and residential construction in the US Pacific Northwest and Southeast. SimaPro 7 was developed in the Netherlands and has an installed Franklin Associate database that uses North America production data. The Franklin Associate database tracked energy use and material flow in this study.

SimaPro allowed the use of the unit process approach in this LCI project which is more rigorous and transparent than the simple system process approach. This transparency allows the tracking of all individual unit processes. Simapro contains a database for a large number of processes such as boilers (energy generation), grid electricity, and transport fuels. The database is broken down into three main sections: project data, library data, and general data. In this LCI study, the project data section is where all the new data were inputted. Library data were the sources for an individual project and the Franklin Associate database library was selected for this LCI. The last section (general data) contained common data such as substance data and unit conversion factors (Pré Consultants 2006).

Methodological Limitations

As mentioned previously, there are some limitations that need to be addressed prior to conducting a LCI study. Detailed explanations were given in the stated Project Assumption sections under Methodology on how these limitations were addressed.

Data Gaps

Primary data were collected from specific facilities per CORRIM research guidelines for all material that constituted at least 95% of the product system, hardwood lumber. Where appropriate, missing primary data from the hardwood lumber questionnaire were not used to weight average (de Beafort-Langeveld *et al* 2003, CORRIM 2004, ISO 2005).

Need for Reliable and Robust Results

Data representation was critical for showing the degree to which the data reflected the actual state of the industry. Species composition, time and length of study, geographical area, and type of technology were stated to show the similarities of the actual industry to the mill data gathered (de Beafort-Lnageveld *et al* 2003).

Providing a detailed and transparent method that follows the CORRIM methodology used in previous studies allows an independent researcher to reproduce the given results. Using the SimaPro software program provides the necessary transparency while displaying results in different formats, depending on what is needed by the user. Also, SimaPro provides an extensive manual on operating the software and the background on how the program was developed (PRė Consultant 2007).

Confidentiality

The absolute confidentiality for all mill participants who provided sensitive production data was strongly stressed both orally and in writing. Confidentiality may have been the main reason some mills declined to contribute their mill data for the LCI study even if the mill owners understood the benefits. Some mill owners talked directly to us on this issue to ensure their information was kept confidential. Only the participating hardwood lumber mill members, Professor Bowe, and I knew what mill data was provided. No mill owner knew the production details of the other participating mills. All the primary mill data were aggregated and weight averaged to a per unit basis of one cubic meter planed dry hardwood lumber (de Beafort-Langeveld *et al* 2003, CORRIM 2004, ISO 2005).

RESULTS and DISCUSSION

Material Flow

Mass and energy values, including emissions for hardwood lumber production, were found by surveying 20 mills in the northeastern United States with detailed questionnaires on mass flow and energy consumption. Survey data were modeled in SimaPro 7 to find non-wood raw material use and emission data.

All energy and material values were weight averaged from 20 mills across 20 states in the northeastern United States (Figure 3) using a spreadsheet. For the 20 mills, 305 million BF rough green lumber was produced in 2005 out of a total production from this region of 5,100 million BF. This value is roughly 6% (USCB 2006a) of the total United States' annual 2005 production that exceeded the minimum ISO protocol requirement for data representation (ISO 1998). Also, 180 million BF and 130 million BF of rough dry lumber and planed dry lumber, respectively, were produced. Not all sawn lumber was dried or planed prior to shipping.

For the mass balance, the LCI study examined the four unit processes and the overall process to track material flow. Overall, 1,170 oven-dried (OD) kg (2,633 OD lb) of incoming hardwood logs with a density of 854 kg/m^3 (53.9 lb/ft^3) produced 1.0 m^3 (637 bf) of planed dry lumber (Table 1). Sawing produced 712 OD kg of rough green lumber; the drying process did not result in any loss of wood substance. Planing reduced the 712 OD kg of rough dry lumber to 535 OD kg of planed dry lumber, for a 25% reduction in mass. Input and output sums of 1,301 and 1,311 of the sawing process indicated the difference in calculating the oven-dry mass of incoming logs and the green lumber and the associated green wood residue separately. Boiler process input sum of 217 followed closely to the difference sum shown in the last column. Overall, the log was reduced to 45.8% of its original mass to produce the final product of planed dry lumber.

Table 1 Overall wood mass balance for 1.0 cubic meter of planed dry lumber (oven dry kilogram)

	Sawing Process		Boiler Process	Drying Process		Planer Process		All Processes Combined		
Material	Input	Output	Input	Input	Output	Input	Output	Input	Output	Diff
(oven-dried kg)[1]										
Green logs	1170							1170	0	-1176
Green chips		227	30.3					30	227	196
Green sawdust		189	140					140	189	49
Green bark[2]	131	139	0.5					132	139	7.9
Green hog fuel		45	18.4					18	45	26
Rough green lumber		712		712				712	712	0
Rough dry lumber					712	712		712	712	0
Planed dry lumber							535	0	535	535
Dry shavings			0				86	0	86	86
Dry sawdust			27.4				46	27	46	19
Dry Mixings			0				44	0	44	44
Sum	**1301**	**1311**	**217**	**712**	**712**	**712**	**712**	**2941**	**2735**	**-206**

[1] Values given in oven-dry weights
[2] Bark volume is not included in log scale

Mills are concerned with their lumber recovery factor. Therefore the volume reduction was determined. Most mills in the United States use volumetric values such as board feet to purchase and sell their products. In the Northeast, 2.29 m^3 (142 ft^3) of hardwood logs were sawn, dried, and planed into the final product of 1.0 m^3 (658 nominal bf) planed dry lumber for a total volume conversion of 43.7% of incoming logs (Table 2). The change in volumes between the rough green and rough dry lumber was due to shrinkage.

Table 2 Volume conversion of incoming logs to 1.0 cubic meter of planed dry lumber

	Wood Volume (actual dimensions)[1,2]		
	(m^3 per 1.0 m^3)	(ft^3 per MBF)[3]	(%)
Raw Wood Material			
Incoming green log	2.29	142	100%
Rough green lumber	1.46	90.9	63.9%
Rough dry lumber	1.37	84.9	59.6%
Final Product			
Planed dry lumber	1.00	62.2	43.7

[1] All values provided in actual dimensions.
[2] Final planed dry lumber dimensions of 19.1 mm (0.75 in) thick by 14.0 mm (5.5 in) wide
[3] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber

Energy Consumption

Hardwood lumber production requires both electrical and thermal energy for processing logs into planed dry lumber. All thermal energy was produced on-site from both wood and fossil fuels whereas most electricity (grid electricity) was produced off-site. Electrical energy is required by all four unit processes while most thermal energy is required by the drying process. Total electrical consumption was 608 MJ per 1.0 m^3 (297 kWh per MBF) planed dry lumber. This includes both off-site and on-site electrical sources (Table 3). For the unit processes, sawing, drying, energy generation (boiler operation), and planing consumes 50%, 25%, 5%, and 20% of the total electricity used, respectively. Based on these percentages, the four unit processes use 304, 152, 31, and 121 MJ per cubic meter or 148, 74, 15, and 60 kWh per MBF planed dry lumber produced, respectively.

Table 3 Overall fuel and electricity consumption on-site to produce a per unit basis of planed dry lumber

Fuel Type	Quantity	SI Units per m^3	Quantity	Units per MBF[5]
Fossil Fuel[1]				
Natural Gas	16.4	m^3	1.02	1000 ft^3
Fuel Oil #1	0.02	L	0.009	gal
Fuel Oil #2	2.08	L	0.964	gal
Fuel Oil #6	0.01	L	0.004	gal
Propane	1.21	L	0.560	gal
Electricity[2]				
Off-site generation	597	MJ	292	kWh
On-site generation	10.2	MJ	5.0	kWh
On-Site Transportation Fuel[3]				
Off-Road Diesel	6.65	L	3.05	gal
Propane	0.267	L	0.124	gal
Gasoline	0.571	L	0.265	gal
Renewable Fuel[4]				
On-site Wood Fuel	217	kg	478	lb
Purchased Wood Fuel	35.4	kg	78	lb

[1] Energy values were found using their higher heating values (HHV) in MJ/kg: 54.4 for natural gas, 43.3 for fuel oil #1 and #2, 45.5 for fuel oil #6, and 54.0 for propane (LPG)
[2] Conversion unit for electricity is 3.6 MJ/kWh
[3] Energy values were found using their higher heating values (HHV) in MJ/kg: 45.5 for off-road diesel and 54.4 for gasoline
[4] Values given in oven-dried weights (20.9 MJ per OD kg)
[5] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber

The thermal energy required for drying and other heating processes, including walnut steaming, cogeneration, and facility heating, was based on fuel consumption with the major source being wood fuel produced on-site from the sawing process. A portion of wood fuel produced on-site (217 OD kg) and some purchased wood fuel (35.4 OD kg) was combusted to generate heat per 1.0 m^3 planed dry lumber for the mill. Thermal energy produced on-site makes up the largest proportion of energy used on-site. Overall, wood fuel comprised 87% of total energy consumed on-site with the next largest contributor being natural gas at 11%. Coal was the largest source of energy used off-site (beyond the mill's boundary) because most grid electricity is from coal power plants in the northeastern United States.

On-site transportation of wood stock was a major fuel consumer, with off-road diesel having the highest consumption. Propane and natural gas are also used for forklifts, front-end loaders, trucks, and other equipment within the system boundary of the facility. Off-road diesel consumption is 6.57 liters (L) per unit basis of planed dry lumber and is consumed at ten times the rate of either propane or gasoline on average. Fuel consumption is broken down for the unit processes into the following percentage; 60%, 10%, 10%, and 20% for sawing, drying, energy generation, and planing. The corresponding values of the four processes for off-road diesel are 3.94, 0.66, 0.66, and 1.31 L, respectively.

The location of the hardwood lumber facility affects the environmental impact because most electricity used is generated by the electric power industry. For example, the Pacific Northwest region produces most of their electricity from hydro (Milota et al 2005). In this study, average composition of (off-site) electrical generation was found for the Northeast by totaling the amount of the different fuel sources for each of the 20 states given in thousand kWh and calculating the percentages (USDOE 2006). The most significant electrical power contributor in the northeastern region was coal, with 58.0% of total electrical utility power being provided by this fuel source. Other fuel sources are nuclear (23.7%), natural gas (10.3%), petroleum (3.4%), hydro (2.7%), and other renewable resources (1.9%) (Appendix C).

Environmental Impact

SimaPro 7 modeled output factors during the manufacturing process with major consumption for raw materials, outside of wood, from electrical generation. Wood, coal, and natural gas are the largest contributors with the values of 51.2, 36.9, and 15.5 kg, respectively, for energy consumption and 1,218 OD kg of wood used in processing (Table 4). Most of the coal and natural gas was used to produce off-site electricity but some was for producing transportation fuel used on-site. The region selected for production affects the environmental impact of hardwood lumber production because coal is the off-site material used most for electrical power in the Northeast, whereas most power in the Pacific Northwest is produced from hydro and then natural gas.

Table 4 Raw materials consumed during production of a per unit basis of planed dry lumber

Raw Material	Quantity[1]	SI Units per m^3	Quantity	Units per MBF[2]
Wood, unspecified, standing[3]	1.43	m^3	88.5	ft^3
Water, well, in ground	0.15	m^3	9.43	ft^3
Wood and wood waste	26.2	kg	101	lb
Coal, in ground	35.3	kg	137	lb
Gas, natural, in ground	14.4	kg	55.7	lb
Oil, crude, in ground	8.16	kg	31.6	lb
Limestone, in ground	5.34	kg	20.7	lb
Energy, from hydro power[4]	11.5	MJ	5.6	kWh
Energy, unspecified[4]	8.12	MJ	4.0	kWh
Uranium, in ground	0.00093	kg	0.00361	lb

[1] Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium
[2] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber
[3] Amount of wood in lumber form entering the planing process
[4] Conversion units for electricity is 3.6 MJ/kWh

Actual emission rates from facilities can be used to determine regulatory policies. Carbon dioxide and particulates are typically measured although other emissions are frequently monitored to ensure compliance. Carbon dioxide (CO_2) emissions are separated into two fuel sources: biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Biogenic CO_2 is carbon-neutral because the CO_2 emitted is reabsorbed during the growth of the tree and released upon the decomposition or burning of the tree. Anthropogenic CO2 is not considered renewable thus carbon-neutral. Emission values of 428 and 139 kg were modeled from SimaPro for CO_2 (biogenic) and CO_2 (anthropogenic), respectively (Table 5) based on material flow and energy type and consumption. Research into measuring volatile organic gases (VOC) produced from drying lumber generated the value of 1.20 kg and is species, temperature, and moisture dependent, with the highest VOC emissions from red oak (Rice and Erich 2006).

Table 5 Life-Cycle Inventory results for total emissions on a per unit basis of planed dry lumber

Substance	Allocated total		Allocated on-site	
	kg/m^3	lb/MBF[1]	kg/m^3	lb/MBF[1]
Water Emissions				
Biological Oxygen Demand (BOD)	9.62E-04	3.73E-03	1.62E-04	6.29E-04
Cl^-	4.05E-02	1.57E-01	1.01E-03	3.93E-03
Suspended Solids	6.96E-02	2.70E-01	1.12E-02	4.36E-02
Oils	1.58E-02	5.89E-02	6.42E-04	2.49E-03
Dissolved Solids	8.90E-01	3.45E+00	3.75E-02	1.46E-01
Chemical Oxygen Demand (COD)	1.28E-02	4.97E-02	5.78E-03	2.24E-02
Soil Emissions				
Waste in inert landfill	7.53E+00	2.92E+01	7.53E+00	2.92E+01
Waste to recycling	2.24E-01	8.69E-01	2.24E-01	8.69E-01
Solid Waste	3.57E+01	1.38E+02	1.72E+01	6.67E+01
Air Emissions				
CO	3.13E+00	1.21E+01	2.84E+00	1.10E+01
CO_2 (biomass)	4.28E+02	1.66E+03	3.98E+02	1.54E+03
CO_2 (fossil)	1.39E+02	5.37E+02	4.65E+01	1.80E+02
CH_4	2.73E-01	1.06E+00	3.96E-03	1.54E-02
Non-methane, volatile organic compounds (NMVOC)	2.32E-01	9.00E-01	6.87E-02	2.66E-01
NOx	1.02E+00	3.97E+00	6.37E-01	2.47E+00
Particulate (Total)	1.16E+00	4.49E+00	1.16E+00	4.49E+00
Particulate (PM10)	7.35E-02	2.85E-01	5.33E-02	2.07E-01
Particulate (unspecified)	9.05E-02	3.51E-01	1.40E-03	5.43E-03
SOx	1.15E+00	4.46E+00	7.46E-02	2.89E-01
VOC	1.20E+00	4.67E+00	1.20E+00	4.67E+00

[1] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber

Carbon Balance

Carbon emissions play an increasingly important role in policy decision-making in the United States and throughout the world. The impact of carbon was determined by estimating values of carbon found in wood and bark as described from previous studies such as Skog and Nicholson (1998) using a mixture of hardwood roundwood values for the northcentral and northeast United States. Carbon input was 914 kg per m^3 planed dry lumber and the total output was 908 kg per unit basis (Table 6), resulting in a percentage difference of 0.71%.

Table 6 Tracking of wood-based carbon inputs and outputs for hardwood lumber

	Elemental Carbon	
Substance[1]	(kg/m3)	(lb/MBF)[2]
Input		
Logs	670	2,600
Bark	75	291
Wood fuel	170	482
Sum carbon in	914	3,370
Output		
Planed dry lumber	306	1,190
Co-products	444	1,722
Solid emissions	0	0
Air emissions	157	349
Sum carbon out	908	3,260

[1] Wood-related carbon and its emissions
[2] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber

Sensitivity Analysis

To satisfy Objective 2 of this LCI study, a sensitivity analysis was completed to model the effects of using different quantities of fuel sources for thermal energy generation. A sensitivity analysis can be useful to understand how various process parameters contribute to environmental output factors. For instance, in hardwood lumber manufacturing; heat is used in several sub-processes, consuming a combination of wood and natural gas as fuel to generate the heat. Changing fuel sources, also referred to as fuel switching, can have a significant effect on the type and quantity of emissions. This sensitivity analysis compared the effects of using all on-site produced wood fuel—consisting of mostly green sawdust and green chips from the sawing process—or natural gas as a fuel input.

For the “base” fuel mix in this LCI study, there were four fuel sources with wood fuel and natural gas contributing the majority of the energy. Propane and fuel oil contributed about 2% with the bulk being used for facility heating. The original model based on survey data assumed 87.2% of the fuel used was in the form of wood fuel, with 74.4% produced on-site and the rest purchased, and 10.8% as natural gas. Most mills use only one or two types of fuel source, whereas the original study resulted in an average model incorporating different fuel sources taken from primary mill data for the 20 mills. There were two alternative fuel use schemes to this “average mill” to be used in this sensitivity analysis. One alternative was assuming total on-site wood fuel use by increasing the initial value of 240 to 300 OD kg for the all (100%) wood fuel case to generate 5,800 MJ of energy per cubic meter (9.66 million BTU per MBF) of planed dry lumber. The second alternative had natural gas use increase from 16.4 to 151 m^3 for the all (100%) natural gas case.

This sensitivity analysis examined three scenarios for heat generation using the base fuel mix, all (100%) natural gas, and all (100%) on-site produced wood fuel cases. These three scenarios were modeled: 1) comparing all (100%) natural gas to the base hardwood lumber model, with no fuel changes and incorporating both natural gas and wood fuel, 2) comparing all (100%) on-site produced wood fuel to the base hardwood lumber model, with no changes, and 3) comparing all (100%) natural gas to all (100%) on-site produced wood fuel as energy for heat.

Sensitivity Analysis Results

Table 7 is a summary of the three fuel use scenarios, with a partial list of air emissions for the Northeast. In the scenarios 1 and 2, a negative percentage difference number indicated that the alternative fuel source released fewer emissions than did the base model. A positive percentage difference means that the “base” or original model releases fewer emissions. Scenario 1 indicated that less particulate and biogenic CO_2 but more fossil CO_2, SOx, and NOx were produced when burning 100% natural gas compared to the base fuel mix (original). Scenario 2 showed the opposite as more biogenic CO_2 and particulate but less fossil CO_2, SOx, and NOx were produced when burning 100% wood fuel compared to the base fuel mix (original). In scenario 3, a negative number indicates that the all natural gas case releases fewer emissions than all on-site produced wood fuel case and a positive percentage number means that all on-site produced wood fuel model releases fewer emissions. Scenario 3 highlighted the difference when larger amounts of wood fuel was consumed as the amount of fossil CO_2, SOx, and NOx produced increased from Scenario 1 but less particulate and biogenic CO2 was produced when compared to Scenario 2. For all three scenarios, the amount of VOC produced was significantly different regardless of the fuel used because most VOC originated in the actual drying of the hardwood lumber.

Table 7 Sensitivity Analysis for manufacturing hardwood lumber in the Northeast

	Fuel Distribution[1]			Scenario 1	Scenario 2	Scenario 3
Substance	100% Natural Gas	100% Wood Fuel	Original	100% Natural Gas to Original Difference (%)	100% Wood Fuel to Original Difference (%)	100% Natural Gas to 100% Wood Fuel Difference (%)
	kg per cubic meter planed dry lumber					
Acetaldehyde	1.14E-06	7.34E-04	6.12E-04	-199.3%	18.2%	-199.4%
Benzene	1.13E-06	8.82E-04	7.35E-04	-199.4%	18.2%	-199.5%
CO_2 (biogenic)	8.50E-02	5.14E+02	4.28E+02	-199.9%	18.3%	-199.9%
CO_2 (fossil)	3.46E+02	1.08E+02	1.39E+02	85.3%	-24.7%	104.5%
CO	7.97E-01	3.63E+00	3.13E+00	-118.9%	14.7%	-128.0%
Formaldehyde	3.48E-03	5.90E-03	5.40E-03	-43.2%	8.8%	-51.5%
Methane	8.98E-01	1.99E-01	2.73E-01	106.8%	-31.3%	127.4%
Naphthalene	1.23E-07	5.87E-04	4.89E-04	-199.9%	18.3%	-199.9%
NOx	1.34E+00	9.94E-01	2.32E-01	140.9%	124.3%	29.6%
Non-methane, VOC	1.12E+00	1.09E-01	1.02E+00	9.2%	-161.3%	164.4%
Organic substances, unspecified	2.10E-03	4.12E-02	3.46E-02	-177.1%	17.3%	-180.6%
Particulate (total)	8.77E-01	1.27E+00	1.16E+00	-27.8%	9.0%	-36.6%
Particulate (PM10)	4.96E-02	7.99E-02	7.35E-02	-38.8%	8.4%	-46.9%
Particulate (unspecified)	8.56E-02	9.33E-02	9.05E-02	-5.6%	3.0%	-8.6%
Phenol	3.71E-06	9.79E-03	8.16E-03	-199.8%	18.2%	-199.8%
SOx	4.50E+00	7.39E-01	1.15E+00	118.6%	-43.5%	143.6%
VOC	1.17E+00	1.22E+00	1.20E+00	-2.2%	1.3%	-3.5%

[1] EPS 2000 V2.02 Method was used in SimaPro 7 to calculate emissions

Environmental Output for the Three Fuel Sources

SimaPro 7 modeled the different fuel sources and provided a graphical display showing the level of environmental impact for the larger air emissions including carbon dioxide from both anthropogenic (fossil fuel) and biogenic (wood fuel) sources. Particulate and carbon monoxide were also shown. There were major shifts quantitatively and qualitatively for both types of carbon dioxide when 100% natural gas (Figure 6) and 100% wood fuel (Figure 7) were used as sole fuel source for heat. The original fuel use is also shown (Figure 8). Actual air emission values are given in Appendix D for all three scenarios on a mass basis.

These Pt values indicate the percentage of environmental impact related to what is referred to as endpoints. Endpoints are used to measure environmental issues such as human health or biodiversity through a series of impact categories. Lower the value of Pt, smaller the environmental damage.

For this particular model, the endpoints are ecosystem production capacity, human health, abiotic stock resource, and biodiversity. Proper selection of impact factors (categories) is critical by showing the link to these endpoints (Pre' Consultants 2006). This SimaPro graphical output uses the combination of following 13 impact categories: life expectancy, severe morbidity, morbidity, severe nuisance, crop growth capacity, wood growth capacity, fish and meat production, soil acidification, production capacity irrigation water, production capacity drinking water, depletion of reserves, and species extinction. Actual values were derived from the four endpoints through these stated impact factors. Measuring the level of environmental impact is expressed in points (Pt).

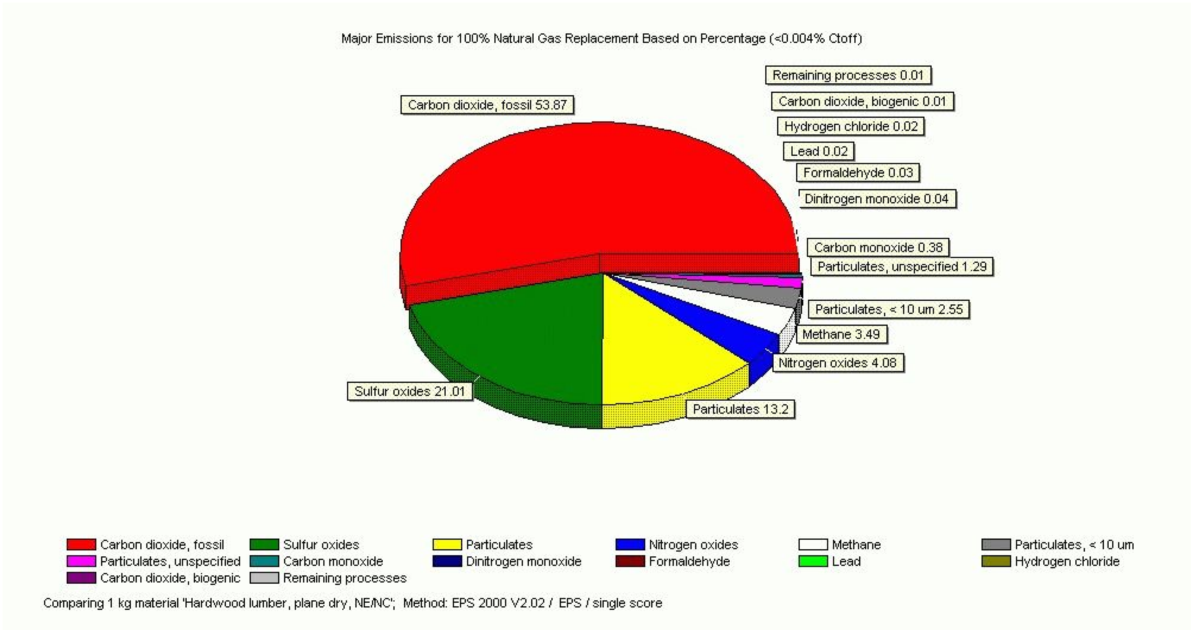

Figure 6. SimaPro 7 model output showing the major air emissions and their level of environmental impact for the 100% natural gas scenario

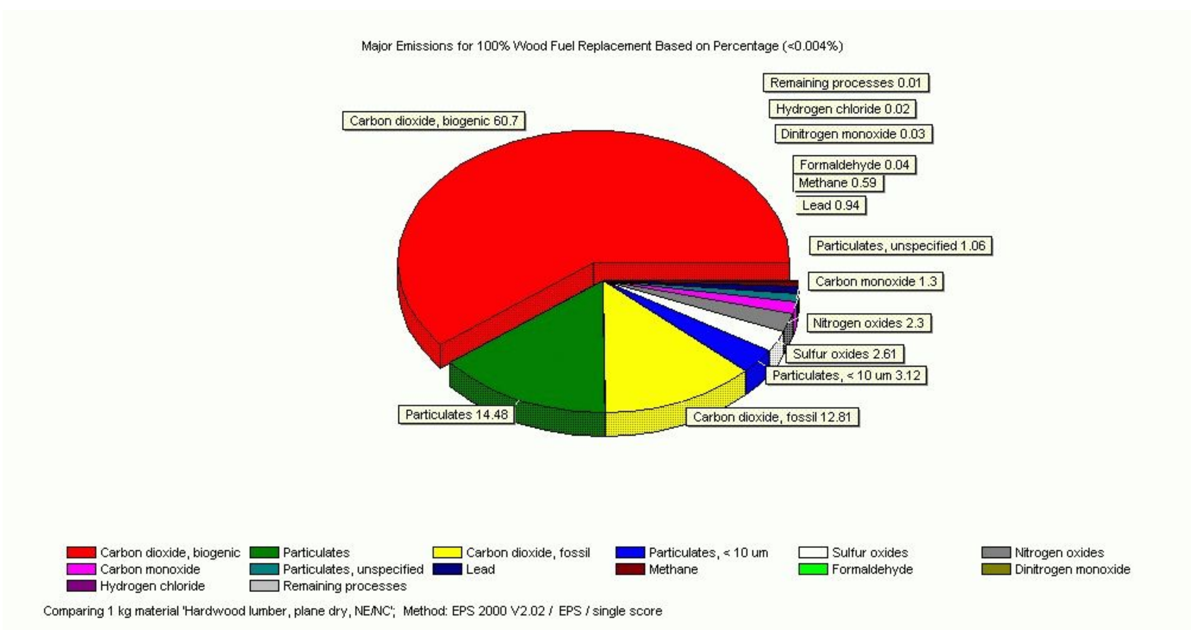

Figure 7. SimaPro 7 model output showing the major air emissions and their level of environmental impact for the 100% wood fuel scenario

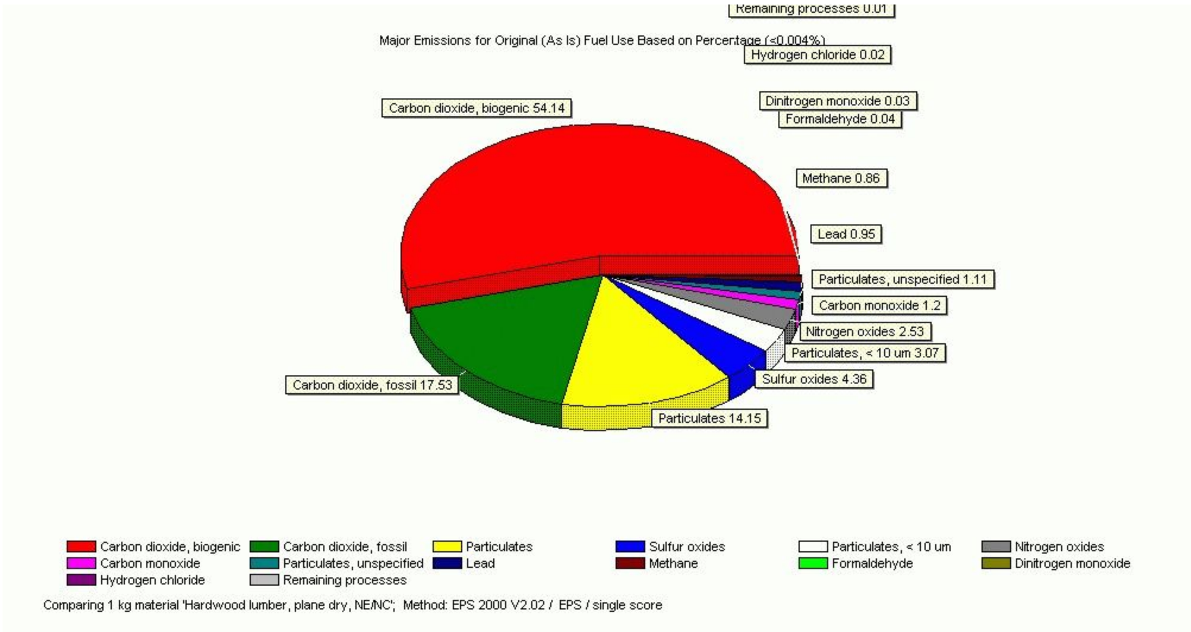

Figure 8. SimaPro 7 model output showing the major air emissions and their level of environmental impact for the orginal (base) fuel scenario

These figures show the actual overall percentage of the environmental damage assigned to each air emissions. Biogenic carbon dioxide was the largest contributor for both the base and 100% on-site produced wood fuel cases. Fossil CO_2 was the largest contributor for the 100% natural gas case.

For the 100% natural gas case, the three largest Pt values assigned in the following order of magnitude were fossil CO_2, sulfur oxides (SOx), and biogenic CO_2 (Figure 9). Comparing this stated case to 100% on-site produced wood fuel (Figure 10); Pt decreases for SOx from 0.0262 to less than 0.0001 and decreases for fossil CO_2 from 0.0673 to 0.0211. The base case falls between these values for both compounds (Figure 11). Also, the value of Pt for particulates increases as the percentage of on-site wood fuel increases.

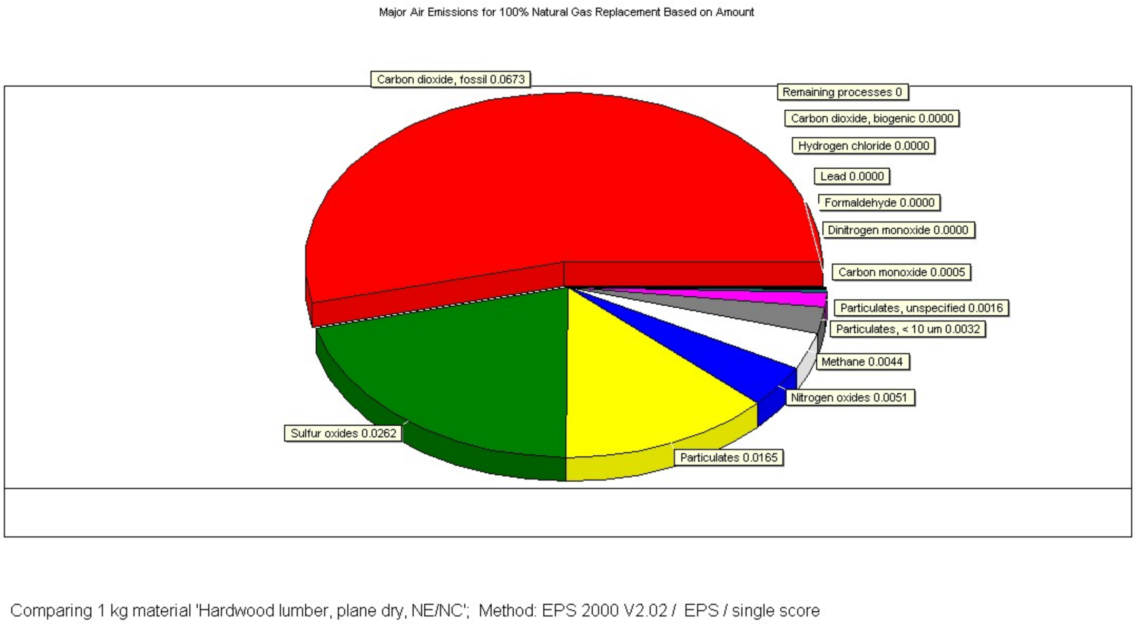

Figure 9. SimaPro model output for major air emissions and their amount of environmental impact for 100% natural gas replacement case

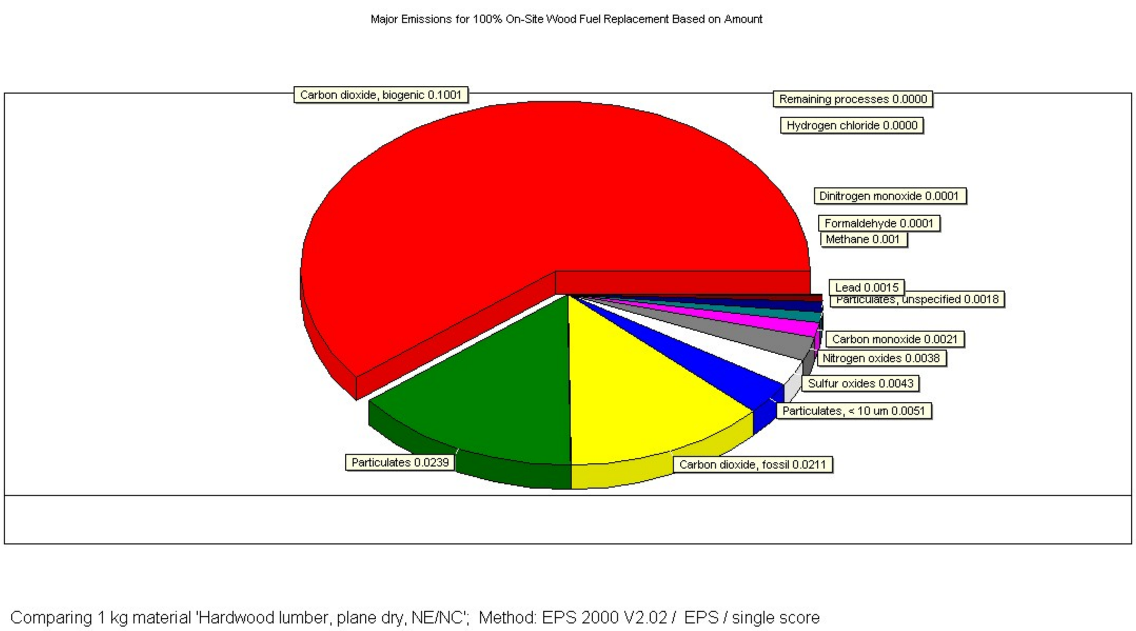

Figure 10. SimaPro model output for major air emissions and their amount of environmental impact for 100% on-site produced wood fuel case

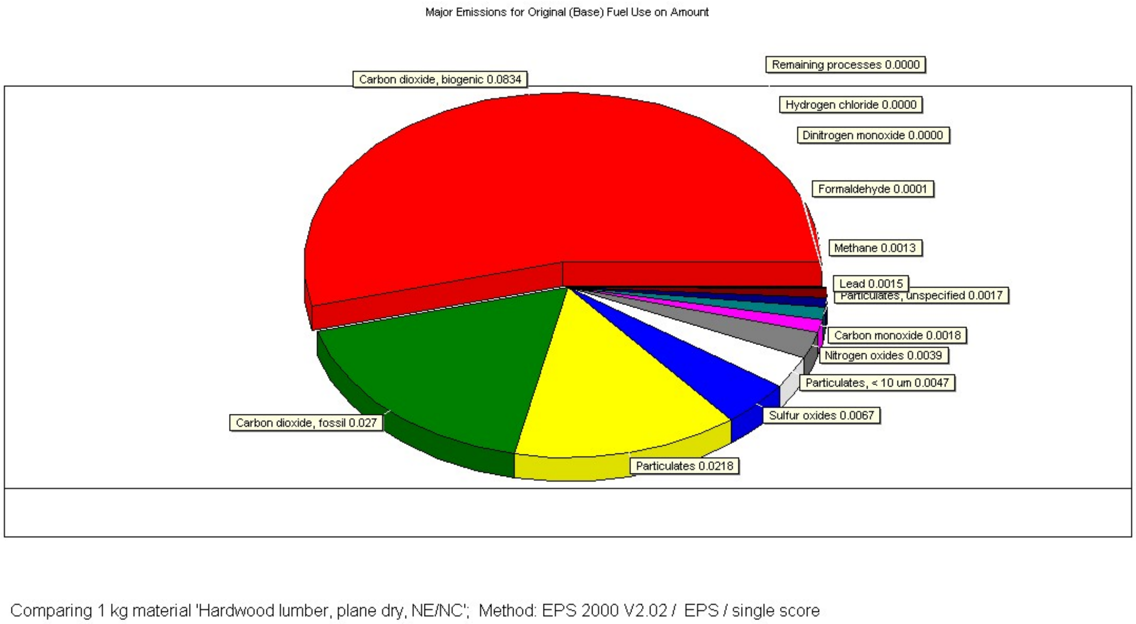

Figure 11. SimaPro model output for major air emissions and their amount of environmental impact for the original (base) fuel case

Based on these results, capturing more particulates from on-site boilers using wood fuel would improve the environmental performance of hardwood sawmills. Furthermore, how SimaPro determined the environmental impact through the four endpoints affects the values of Pt. For example, placing a higher Pt number, 0.1001, for biogenic CO_2 on the 100% on-site produced wood fuel case than the Pt value, 0.0673, for fossil CO_2 on the 100% natural gas needs to further examined considering natural gas is neither renewable nor carbon-neutral unlike wood fuel.

STUDY SUMMARY

A rigorous material and energy balance was completed on 20 hardwood mills located in the northeastern United States. The results indicate that total energy consumption varied significantly, depending on the species sawn, age of the boiler and dry kiln equipment, and method of drying. For hardwood lumber, an average thermal consumption of 5,800 MJ per cubic meter (9.66 million BTU per MBF) and electrical energy use of 608 MJ per cubic meter (297 kWh per MBF) planed dry lumber were found. Two mills produced their own electrical power from the wood residue produced on-site and consumed about four times the amount of wood residue than mills that did not produce their electrical power per unit volume of lumber dried.

Electrical consumption varied significantly, depending on whether the mill used dehumidification, predryers, or air yards to dry lumber. Two mills using dehumidification kilns consumed 45.3% more electrical energy compared to the other mills, although dehumidification kilns used less than 5% of the average thermal energy. Most mills producing red and white oak lumber used predryers and air yards to lower moisture content prior to kiln drying to reduce time in the kilns. Mills running predyers used 64.5% more electricity than did the average mill.

Thermal energy use also varied considerably, depending on whether the mill ran a walnut steamer or a cogeneration unit. Four mills operated a walnut steamer. Thermal energy was reduced by 45.3% for on-site wood fuel use from 151 to 83 OD kg per m^3 planed dry lumber when the mills steaming walnut and producing on-site electricity were not used in calculations. This is significant because wood fuel produced on-site provides about 74% of the total thermal energy required.

LCI projects for softwood lumber production consumed less electrical and thermal energy in their production (Milota et al 2005) compared to hardwood lumber (Table 7). There are several reasons for this. One reason is that hardwood lumber requires longer drying times and more thermal energy is consumed for the same volume of product. Another reason is that hardwood lumber is more likely to be converted to high-grade lumber. Other reasons include the fact that hardwood is generally more dense than softwood lumber and hardwood lumber is sawn thinner as well so more electrical energy is consumed in the sawing process. In this study, the Northeast used more energy to keep the facility heated during winter months compared to the Pacific Northwest and Southeast.

Table 8 Comparison of hardwood to softwood lumber energy use

	Overall Energy Consumption [1,2]			
	Electrical Energy		Thermal Energy	
	(MJ per m^3)	(kWh per MBF)	(MJ per m^3)	(BTU per MBF)
Hardwood Lumber	597	297[3]	5,400	9.6 million[3]
Softwood Lumber	335[4]	151	3,600	5.5 million

[1] All values provided in actual dimensions.
[2] Final planed dry lumber dimensions of 19.1 mm (0.75 in) thick by 14.0 mm (5.5 in) wide
[3] 1.76 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber and includes walnut steaming and plant heating
[4] 1.623 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber; 3.6 MJ per kWh, 1054 MJ per million BTU

Total energy consumption per cubic meter of planed dry hardwood lumber was found to be comparable to published data (Armstrong and Brock 1989; Comstock 1975). However, unlike previous studies, processes such as walnut steaming, facility heating, and cogeneration were examined because their energy use was significant. Wood has two significant advantages over non-wood substitutes; wood is carbon-neutral and carbon can be sequestered (captured and stored). Therefore, using wood as a fuel or in a finished wood product from hardwood lumber could be considered a sustainable practice. Other non-wood products typically do not have the benefits of a carbon-neutral product to use both as a fuel and a finished product. Also, decreasing energy consumption would be of great benefit to the mills, especially in sawing and drying.

There are several approaches to lowering energy consumption, and the mills that incorporate these methods would ultimately have significantly lower energy use. The most energy efficient method would be upgrading or refurbishing the mill's aging dry kiln facilities at mills currently using more than 1.5 times the amount of energy per MBF than the mill using similar drying technology with similar specie composition. This may also improve lumber quality because the newer dry kilns will probably have greater precision and accuracy in maintaining kiln temperatures and fan speeds. Sawing lumber manually (without computer assistance) may increase sawing errors, and thus sawing time and electrical costs. Using improved sawing practices such as the Best Opening Face program (Harpole and Hallock 1977) and thinner saw kerfs have increased lumber yields while lowering electricity consumption.

Another approach reduces thermal energy use. Several different drying methods can be used depending on species, fuel costs, and wood residue use. Air drying lumber is one such method but has not been the preferred method of drying due to drying degrade and large quantity of drying stock required except for slow-drying species like red and white oak. Drying degrade is a reduction in lumber quality caused by drying; greater control of the drying process typically reduces drying degrade. Maintaining a large lumber inventory for air drying reduces profits due to delays in recovery investments. Air drying lumber has the lowest control among the different drying methods, resulting in the highest level of degrade although it provides the lowest energy use of all drying methods.

CONCLUSIONS

Based on the Life-Cycle Inventory results, the following conclusions are drawn:

- More on-site wood fuel consumption would reduce fossil greenhouse gases but increases other gases and particulate.
- Increasing the level of air drying lumber prior to kiln drying, especially for species where color is not a problem, would lower the amount of energy required for the drying process. Therefore improving air drying methods would lower energy use while maintaining lumber quality and reducing the environmental impact of hardwood lumber.
- Sawing consumes the highest proportion of electricity in the manufacturing of hardwood lumber. Thus, installing optimization equipment would lower electrical consumption by reducing sawing errors and time.
- Drying consumes the highest proportion of fuel. Lower overall energy consumption by upgrading or overhauling existing old and inefficient dry kiln facilities.
- Once the competing non-wood substitutes have been inventoried, product selection for sustainable building could be used to compare vinyl to hardwood moulding or carpet systems to solid hardwood flooring.

Caution is required when using wood product LCI studies and the final LCA for comparison to non-wood products. It may be more important to know exactly how much material is needed for the same use instead of basing comparisons on a volume or mass basis. An example would be how much hardwood flooring would be needed compared to a carpet system with a sub-floor. Floors and carpets are measured in square feet and yards, respectively, in the United States. This study results give all values based on a cubic meter; therefore, thickness of material is a critical dimension for consideration.

Another problem is distortion of data or taking results out of context without considering the true overall environmental effect. Some marketing methods will only highlight certain aspects of their products while minimizing others. Most likely, misuse of LCI studies will cause a loss of faith in the LCA method unless strict guidelines are developed and adopted.

LITERATURE CITED

ARMSTRONG, J.P., AND S.M. BROCK. 1989. Predicting fuel consumption of central Appalachian kiln-drying enterprises. Forest Prod. J. 39(3):57-61

BENEDICK, RICHARD E. 2000. Human Population and Environmental Stresses in the Twenty-first Century. Environmental Change & Security Project Report, Issue 6 (Summer 2000) pp.18

BOYD, C.W., P. KOCH, H.B. McKEAN, C.R. MORSCHAUSER, S.B. PRESTON, AND WANGAARD, F.F. 1976. Wood for structural and architectural purposes. Wood Fiber Sci. 8 Special CORRIM Panel II Report :pp. 3-72

BOWYER, J., J. HOWE, P. GUILLERY AND K. FERNHOLZ. 2005. Life-Cycle Analysis: A Key to Better Environmental Decisions. Dovetail, Inc. 10 pp.

COMSTOCK, G.L. 1975. Energy requirements for drying of wood products. *In:* Wood Residues as an Energy Source. Proc. No. P-75-13: 8-12

CONSORTIUM FOR RESEARCH ON RENEWABLE INDUSTRIAL MATERIALS (CORRIM). 2004. Research Guidelines for Life-Cycle Inventories. CORRIM, Inc. University of Washington, Seattle, WA. April. 47 pp.

DE BEAFORT-LANGEVELD, A.S.H, R.BRETZ, R. HISCHIER, M. HUIJBREGTS, P. JEAN, T. TANNER, AND G.VAN HOOF. 2003. Code of Life-Cycle Inventory practices. Penscola, FL., USA: Society of Environmental Toxicology and Chemistry (SETAC). 160 pp.

DENIG, J., E. M. WENGERT, AND W. T. SIMPSON. 2000. Drying hardwoods lumber Gen. Tech. Rep. FPL-GTR-118. USDA Forest Service, Forest Products Laboratory, Madison, WI.138 pp

DUDA, M., AND J.S. SHAW. 1997. From Cradle to Grave: Measuring Products' Environmental Impact. USA Today Magazine. Volume124, Issue 2624, pp 54 ff. Editorial.

FOREST PRODUCTS LABORATORY (FPL). 1999. Wood handbook: Wood as an engineering material. Gen. Tech. Rep. FPL-GTR-113. USDA Forest Service, Forest Products Laboratory, Madison, WI. 463 pp.

HARDWOOD MARKET REPORT (HMR). 2006. 2005: The year at a glance. 9th annual statistical analysis of the North American hardwood marketplace. HMR. Memphis, TN. 168 pp.

HARPOLE, G. B., AND H. HALLOCK, 1977. Investment opportunity: Best opening face sawing. USDA Forest Serv. Res. Pap. FPL 291. 9 pp.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO). 1998. Environmental management—Life-Cycle assessment—goal and scope definition and inventory analysis. ISO 14041. First Edition 1998-10-01. Geneva, Switzerland. 26 pp.

________. 2005. Environmental management—Life-Cycle assessment—Requirements and guidelines. ISO 14044. Draft International Standard. Geneva, Switzerland. 45 pp.

LIPPKE, B., J. WILSON, J. PEREZ-GARCIA, J. BOWYER, AND J. MEIL. 2004. CORRIM: Life-Cycle Environmental Performance of Renewable Building Materials. Forest Prod. J. Vol. 54, No. 6. pp. 7-19

McGRAW HILL CONSTRUCTION (MHC). 2006. Green Building Smartmarket Report. New York, NY:. HD9715.U5 G69

MILOTA, M. R., C. D. WEST, AND I. D. HARTLEY. 2005. Gate-to-gate life inventory of softwood lumber production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 47-57

NATIONAL HARDWOOD LUMBER ASSOCIATION (NHLA). 2007. Rules for the Measurement & Inspection of Hardwood & Cypress. NHLA. Memphis, TN. 104 pp.

NATIONAL RENEWABLE ENERGY LABORATORY (NREL). 2007. Life-Cycle Inventory database project. http://www.nrel.gov/lci/. (27 Feb 2007).

PEUTTMANN, M.E. AND J.B. WILSON. 2005. Gate-to-gate Life-Cycle Inventory of glue-laminated timbers production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 99-113

PRÉ CONSULTANTS. 2006. Introduction to LCA with SimaPro 7. March 2006. Plotter 12, 3821 BB Amersfoort, The Netherlands. pp. 92

_____________. 2007. SimaPro 7 Life-Cycle assessment software package, Version 7. Plotter 12, 3821 BB Amersfoort, The Netherlands. http://www.pre.nl/. (27 Feb 07).

RICE, R.W. AND M. SUSAN ERICH. 2006. Estimated VOC Losses During the Drying of Six Eastern Hardwood Species. Forest Prod. J. Vol. 56, No. 10. pp. 48-51

SKOG, K.E. AND G.A. NICHOLSON. 1998. Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. Forest Prod. J. Vol. 48, No. 7/8. pp. 75-83

SPELTER, H. 2002. Conversion of board foot logs to cubic meters in Washington State, 1970-1998. General Technical Report FPL-GTR-131. Madison, WI: USDA Forest Service, Forest Products Laboratory.

UNITED STATES DEPARTMENT OF ENERGY (USDOE). 2006. Net Generation by Energy Source by Type of Producer. http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls (15 January 2007)

UNITED STATES CENSUS BUREAU (USCB). 2006a. Lumber Production and Mill Stocks: 2005. http://www.census.gov/industry/1/ma321t05.pdf (10 October 2006)

UNITED STATES CENSUS BUREAU (USCB). 2006b. New Residential Construction Index: 2006. http://www.census.gov/const/www/newresconstindex.html (19 March 2007)

WENGERT, E.M. 1980. How to reduce energy consumption in kiln-drying lumber. Research Note FPL-RN-0228. Madison, WI: USDA Forest Service, Forest Products Laboratory.

WILSON, J.B., AND E.T. SAKIMOTO. 2005. Gate-to-gate Life-Cycle Inventory of softwood lumber production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 58-73

________, AND E.R. DANCER. 2005. Gate-to-gate Life-Cycle Inventory of I-joist production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 85-98

________, AND E.R. DANCER. 2005. Gate-to-gate Life-Cycle Inventory of laminated veneer lumber production. Wood Fiber Sci. 37 CORRIM Special Issue:pp. 114-127

APPENDICES

Appendix A - Page 1: Primary Mill Data questionnaire: Introduction and Questionnaire

Hardwood Sawmill Analysis Project

Thank you for giving me the opportunity to work with you on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be a good marketing tool for the U.S. hardwood industry particularly the green building industry. A growing demand for building projects that use environmentally friendly and energy-efficient materials has spurred a green movement in the construction industry. An estimated $10 billion of "green buildings" are in the process of construction this year in the United States.

This research will test the theory that using wood in more applications that substitute for non-renewable products can substantially improve environmental performance, thus increasing the marketability of forest products. As you know, wood offers unique opportunities to store carbon in the forest, products, and substitution (avoided fossil fuel intensive products) while also supporting other ecological services such as clean water, clean air, habitat, and recreation.

Based on the Eastern Region (all states bordering as well as east of the Mississippi River), my final report will describe a gate-to-gate analysis of hardwood sawmills. The information collected will show the comparison of wood versus non-wood materials on an energy, economic, and environmental basis. Regarding the questionnaire, our primary focus is on overall mill information because this data is vital for precise and accurate results. Details harder to report will be requested later so I encourage you to call with specific questions.

Questions will be focused on annual production, energy use and generation, material inputs, and environmental emissions. We realize that you may not have all the information requested, but the data you are able to provide will be appreciated. **Strict confidentiality** will be maintained for all the companies that supply the data for this project. Please complete the following questionnaire by **November 30, 2006**.

Company Name: ______________________________

Mill Address: ______________________________

____

Contact Person: ______________________________

Position/Title: ______________________________

Telephone: ____________ **Fax:** ________________

Questions should be directed to:

Rick Bergman – Wood Drying Researcher
University of Wisconsin - Wood Products Program
120 Russell Labs
1630 Linden Dr
Madison, WI 53706
Phone (608) 231-9477 / FAX (608) 231-9303
rbergman@wisc.edu

Appendix A - Page 2

This report is part of a larger initiative sponsored by Consortium for Research on Renewable Industrial Materials (CORRIM) to provide a database of information for quantifying the environmental impacts and economic costs of wood building materials through the stages of planting, growing, manufacturing, construction, operational use, and demolition.

Hardwood Sawmill Analysis

We have divided the mill into four unit processes. This division is like drawing a boundary around a part of the process. We want to find out everything that crosses the boundary. We would like to get information on total inputs and outputs from the mill first and then for each unit process where possible; please contact Rick Bergman @ (608) 231-9477 with any questions or concerns.
This questionnaire is divided into six parts.

- Part I deals with a basic description of the mill and its operations.
- Part II requests information on primary mill's total inputs and outputs for each of the following processes
  - Section A - Sawing (logyard and sawmill)
  - Section B - Drying
  - Section C - Planing (planing and packaging of lumber)
  - Section D - Energy generation

Within each of the last four parts, the questionnaire contains series of tables organized as follows:

Inputs
- Materials
- Energy (fuels and electricity)
- Water

Outputs,
- Products
- Air emissions
- Liquid emissions
- Solid waste

Emissions control equipment

Please complete the tables by either hand written or typing responses in the spaces provided. Provide as much detail as possible. Please contact Rick Bergman @ (608) 231-9477 if you have questions.

Space is provided throughout the questionnaire for any additional comments, clarifications or observations you might care to add.

Units are generally specified, but if you have other units that are easier to use, please cross off our units and add yours.

If you do not know the quantities at the level of detail requested, group by category. For example, provide a value for all hazardous air pollutants (HAPs) if the quantities of individual compounds are not known.

Thank you for the time and effort to fill in the blanks. Not all mills have everything on the list and it should be easier than it looks to complete.

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PART I – Operation Overview

Reporting Year:	Starting Month:	Ending Month:

General Mill Information

1. Mill type (please check one):

- ❑ Green lumber mill
- ❑ Dry lumber mill
- ❑ Cant / tie mill
- ❑ Pallet mill
- ❑ Other (specify)____________________

2. Rough Green Lumber Production

For reporting year __________ thousand board feet (BF)

Percent kiln dried __________ %

3. Which of the following does this mill have (check each one that applies)?

- ❑ log storage
  - o dry deck
  - o sprinkled deck
  - o pond
  - o other: _______________
- ❑ log handling
  - o log sorter/merchandizer
  - o debarker
- ❑ sawmill
  - o head rig(s) how many _____
  - o resaws, how many: ______
  - o edgers, how many: ______
  - o edger optimizer
  - o trimmer optimizer
  - o trimmer
  - o sorter, # bins: ______
  - o sticker stacker
- ❑ dryers
  - o predryer
  - o conventional steam (10-15 psig)
  - o high temperature steam
  - o direct-fired
  - o dehumidification
  - o transfer car system
  - o air drying yard
- ❑ boiler
  - o wood-fired boiler
  - o gas-fired boiler (natural or propane)
  - o oil-fired boiler
  - o cogeneration facility
  - o bag house
- ❑ planers
  - o planer
  - o in-line moisture meter
  - o grading station
  - o trimmer
  - o end paint/seal
- ❑ other mill equipment

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PART II – Total Material and Energy Inputs and Outputs

TOTAL LOG/LUMBER INPUTS (Annual Production – see Block Diagram on page 6)

- Logs: ***What type of log scaling is used?*** ____________________

  1. Volume of incoming logs ____________________ thousand BF
  2. Volume sorted & sold to outside firms ____________________ thousand BF
  3. Volume of logs to sawmill (on-site) ____________________ thousand BF

- Rough Green Lumber
  4. Volume from on-site sawmill ____________________ thousand BF
  5. Volume purchased from outside firms ____________________ thousand BF
  6. Volume sorted & sold to outside firms ____________________ thousand BF
  7. Volume from predryers ____________________ thousand BF
  8. Volume from airyard ____________________ thousand BF
  9. Volume to dry kilns ____________________ thousand BF

- Rough Dry Lumber
  10. Volume kiln-dried on-site ____________________ thousand BF
  11. Volume purchased from outside firms ____________________ thousand BF
  12. Volume sorted & sold to outside firms ____________________ thousand BF
  13. Volume to planer ____________________ thousand BF

- Planed Dry Lumber
  14. Volume from planer ____________________ thousand BF
  15. Volume purchased from outside firms ____________________ thousand BF
  16. Volume sorted and sold to outside firms ____________________ thousand BF
  17. Volume used internally (on-site) ____________________ thousand BF

Please complete the following table showing the breakdown of the individual tree species and approximate sizes processed by your mill. If less than 2% of total, use category labeled "Other".

Species	% of total log input into sawmill
Total	100%

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TOTAL (NON-TRANSPORTATION) FUEL USE (see Block Diagram on page 7)

- Wood
  1. On-site wood boiler fuel ______ @ ____ %MC tons
  2. Purchased wood boiler fuel ______ @ ____ %MC tons

- Fossil Fuel
  3. Natural Gas ______________ thousand cubic feet (ft^3)
  4. Fuel oil #1(kerosene) ______________ gallons
  5. Fuel oil #2 (heating oil) ______________ gallons
  6. Fuel oil #6 ______________ gallons
  7. Propane ______________ gallons
  8. Other ______________
  9. Electricity for entire facility ______________ kilowatt-hours (kWh)

TOTAL WATER USE

- Water ______________ gallons or ft^3

TOTAL WOOD CO-PRODUCT/BY-PRODUCT OUTPUT

For each co-product and by-product, please indicate the percentages of total production for the reporting period that are sold (shipped) to other users, used internally (either as fuel or other uses), landfill, or inventoried for future use. Select whatever category best fits your mill's situation. If zero, enter a dash (-).

Co-products and By-Products	Moisture Content	Sold (Shipped)	Used Internally (as fuel)	Used Internally (other uses)	Landfilled	Inventory	Total
	(%)	tons	tons	tons	tons	tons	tons
Chips, green							
Sawdust, green							
Bark, green							
Edging strips, green							
Sawdust, dry							
Shavings, dry							
Hogged material							
Other							

TOTAL INDUSTRIAL (SOLID) WASTE (material requiring disposal outside of mill)

Type	Tons/Pounds	Percent Landfilled
Fly Ash		
Bottom ash		
General refuse		
Recycled material		

Appendix A - Page 6

TOTAL AIR EMISSIONS

Type	Amount (pounds)
Particulate	
PM10	
HAPs	
Others (SO_2, ROG[1], etc.)	

[1]Reactive Organic Gases (also referred to as Volatile Organic Compounds)

TOTAL TRANSPORTATION FUEL USE ON-SITE[2]

Type	Units
On-road diesel	Gallons
Off-road diesel	Gallons
Fuel Oil #6	Gallons
Propane	Gallons
Gasoline	Gallons
Other	

[2]Include all sources of energy such as fuels for yard equipment, forklifts, and carriers

TRANSPORTATION – LOGGING TRUCKS

Mileage logging/lumber trucks travel annually ______________miles
______________% One-way
______________% Empty backhaul

ENERGY GENERATION - BOILER FUEL USE

1. If present, please indicate the actual (not rated) production output of every process boiler:

Boiler	Size (BTU/hr, HP, or lbs/hr of steam[3])	Fuel type	Quantity (units)
#1			
#2			
#3			

[3]If known, list boiler steam pressure

2. If any wood boiler fuel used on-site is ***purchased from off-site sources***, please indicate the amounts by type in the spaces provided below. Otherwise ignore and go to next question. If zero, enter a dash (-). Please make sure you show the **units** of measure.

Boiler Fuel	**Quantity**	**Units** (enter %MC if known)
Shavings, dry		
Sawdust, dry		
Sawdust, green		
Bark, green		
Hogged fuel (mixed grindings)		
Chips, green		

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3. If present, please indicate the cogeneration facility production output:

Electricity (kW or MW)	Process heat (BTU/hr)	Fuel type	% used or sold off site	
			electricity	process heat

EMISSIONS CONTROL EQUIPMENT (ECD)

Include emission control devices (ECD) if any for air emissions such as cyclones, baghouses, and electric static precipitators (ESPs)

For water emissions, explain how runoff or other water discharges from the boiler and logyard are controlled (i.e. handled) such as settling pond, city sewer, septic

		Boiler #1	Boiler #2	Boiler #3	Sawmill	Planermill	Logyard
Type of Device							
Equipment controlled							
Electrical	[1]Usage, kWh						
	included in energy table, Y or N						
Type of emissions controlled							

[1]Or state other units

Glossary

Product = the primary material produced from manufacturing and "sold outside of the system boundary;"
Co-product = a material produced from manufacturing and "sold outside of the system boundary;"
Internal by-product = a material produced during the manufacturing that is recycled or used "within the system boundaries"
Industrial waste = a material produced during the manufacturing that requires "disposal outside of the system boundary"
HAPs = Hazardous Air Pollutants
ROG = Reactive Organic Gases (also referred to as Volatile Organic Compounds (VOCs)
Slabs = the lumber cut on a circular or band head rigs from the outside portions of logs when squaring the log for lumber; does not have square edges
Edgings = these pieces of board that passed through a machine called an edger that can make two or more lineal cuts simultaneously
General refuse = waste collected from the sawmill operation that is mixed with dirt and cannot be sent to the boiler
Recycled material = material collected from the sawmill operation that is recycled
Packaging material = steel strapping, plastic lumber covers, and cardboard corners

Appendix B - 1: First letter sent to Hardwood Manufacturer Association

United States Department of Agriculture **Forest Service** **Forest Products Laboratory** **One Gifford Pinchot Dr. Madison, WI 53726-2398**

File Code: 4700

Date: September 15, 2005

Susan Regan
HARDWOOD MANUFACTURERS ASSOCIATION
400 Penn Center Boulevard, Suite 530
Pittsburgh, Pennsylvania 15235

Dear Susan Regan:

Thank you for giving me the opportunity to discuss with you my project involving the long-term viability and profitability of the U.S. wood products industry. The paper resulting from this project I believe will be a good marketing tool for HMA.

Energy and economic concerns about forests and wood products have a direct and significant impact on U.S. building materials and home building industries. Thus, a scientifically sound national database would be helpful in explaining to anyone interested in the forest products industry the energy and economics of wood building materials versus non-wood building materials. Developing a database report on the material and energy inputs and outputs (i.e., life cycle inventory) through mill surveys of hardwood lumber mills will assist in this process. The area to be covered in the mill survey is the Forest Service Northeastern Region, which covers 20 states,

My report will be useful in learning the true value of forest products in regards to the positive environmental effects and provide an avenue for discussion among interested forest products groups, particularly policymakers. Currently, I am seeking hardwood sawmill owners in Missouri, Michigan, New York, Pennsylvania, West Virginia, and Wisconsin to participate in this confidential mill survey. Any assistance in this matter from you and your membership would be greatly appreciated. The survey will cover the following unit processes: (1) Sawing, (2) Drying, (3) Energy Generation, and (4) Planing. The questions will focus on annual production, energy use and generation, material inputs, product outputs, and other by-products.

Based on the Forest Service Northeastern Region, my final report will describe a gate-to-gate analysis of hardwood sawmills. The information gathered will be added to the national database mentioned above as part of a larger initiative sponsored by the Consortium for Research on Renewable Industrial Materials (CORRIM) (www.corrim.org). This is an organization of 15 research institutions that includes the Forest Products Laboratory. The information I collect will allow the comparison of wood and non-wood materials on an energy, economic, and environmental basis.

My research will test the theory that using wood in more applications that substitute for fossil-intensive products can substantially improve environmental performance, thus increasing the marketability of forest products. As you know, wood offers unique opportunities to store carbon in the forest, products, and substitution (avoided fossil intensive products) while also supporting other ecological services such as clean water, clean air, habitat, and recreation.

I look forward to hearing from you and would appreciate any assistance in seeking mill owners to participate into this research. I plan on attending the Forestry Field Day at Kretz Lumber in Antigo, WI on September 17. Perhaps, we can spend some time then discussing this opportunity.

Sincerely,
Richard D. Bergman
Richard Bergman
Research Chemical Engineer
USDA Forest Service

Caring for the Land and Serving People

Printed on Recycled Paper

Appendix B - 2: Second letter sent to Hardwood Manufacturer Association

United States Department of Agriculture **Forest Service** **Forest Products Laboratory** **One Gifford Pinchot Dr. Madison, WI 53726-2398**

File Code: 4700

Date: July 13, 2006

Susan Regan
HARDWOOD MANUFACTURERS ASSOCIATION
400 Penn Center Boulevard, Suite 530
Pittsburgh, Pennsylvania 15235

Dear Susan Regan:

Thank you for giving me the opportunity to discuss with you my project involving the long-term viability and profitability of the U.S. wood products industry. The paper resulting from this project I believe will be a good marketing tool for HMA.

Energy and economic concerns about forests and wood products have a direct and significant impact on U.S. building materials and home building industries. Thus, a scientifically sound national database would be helpful in explaining to anyone interested in the forest products industry the energy and economics of wood building materials versus non-wood building materials. Developing a database report on the material and energy inputs and outputs (i.e., life cycle inventory) through mill surveys of hardwood lumber mills will assist in this process. The area to be covered in the mill survey is the Forest Service Northeastern Region, which covers 20 states,

My report will be useful in learning the true value of forest products in regards to the positive environmental effects and provide an avenue for discussion among interested forest products groups, particularly policymakers. Currently, I am seeking hardwood sawmill owners in Missouri, Michigan, New York, Pennsylvania, West Virginia, and Wisconsin to participate in this confidential mill survey. Any assistance in this matter from you and your membership would be greatly appreciated. The survey will cover the following unit processes: (1) Sawing, (2) Drying, (3) Energy Generation, and (4) Planing. The questions will focus on annual production, energy use and generation, material inputs, product outputs, and other by-products.

Based on the Forest Service Northeastern Region, my final report will describe a gate-to-gate analysis of hardwood sawmills. The information gathered will be added to the national database mentioned above as part of a larger initiative sponsored by the Consortium for Research on Renewable Industrial Materials (CORRIM) (www.corrim.org). This is an organization of 15 research institutions that includes the Forest Products Laboratory. The information I collect will allow the comparison of wood and non-wood materials on an energy, economic, and environmental basis.

My research will test the theory that using wood in more applications that substitute for fossil-intensive products can substantially improve environmental performance, thus increasing the marketability of forest products. As you know, wood offers unique opportunities to store carbon in the forest, products, and substitution (avoided fossil intensive products) while also supporting other ecological services such as clean water, clean air, habitat, and recreation.

I look forward to hearing from you and would appreciate any assistance in seeking mill owners to participate into this research. I plan on attending the Forestry Field Day at Kretz Lumber in Antigo, WI on September 17. Perhaps, we can spend some time then discussing this opportunity.

Sincerely,
Richard D. Bergman
Richard Bergman
Research Chemical Engineer
USDA Forest Service

Caring for the Land and Serving People

Appendix C - 1: Total Electrical Power Industry by Source for Northeast for 2005 by State – Coal and Other Gases

STATE	ENERGY SOURCE	GENERATION (Megawatthours)
CT	Coal	3,996,492
DE	Coal	4,832,948
IA	Coal	34,252,392
IL	Coal	92,264,272
IN	Coal	122,817,019
MA	Coal	12,033,546
MD	Coal	29,313,922
ME	Coal	322,359
MI	Coal	70,345,630
MN	Coal	32,910,342
MO	Coal	77,437,142
NH	Coal	4,072,987
NJ	Coal	11,625,410
NY	Coal	20,597,682
OH	Coal	136,874,551
PA	Coal	120,938,406
WI	Coal	41,649,010
WV	Coal	91,419,556
SUBTOTAL	Coal	907,703,666
CT	Other Gases	1,566
DE	Other Gases	496,436
IL	Other Gases	198,788
CT	Other Gases	1,566
DE	Other Gases	496,436
IL	Other Gases	198,788
IN	Other Gases	2,702,750
MD	Other Gases	343,168
MI	Other Gases	697,417
MO	Other Gases	2,383
OH	Other Gases	297,392
PA	Other Gases	511,038
WV	Other Gases	84,396
SUBTOTAL	Other Gases	6,032,124

Appendix C - 2: Total Electrical Power Industry by Source for Northeast for 2005 by State – Petroleum and Other

CT	Petroleum	3,156,048
DE	Petroleum	1,216,423
IA	Petroleum	149,537
IL	Petroleum	326,024
IN	Petroleum	279,038
MA	Petroleum	7,119,369
MD	Petroleum	3,817,584
ME	Petroleum	1,611,697
MI	Petroleum	897,881
MN	Petroleum	783,358
MO	Petroleum	168,418
NH	Petroleum	1,357,142
NJ	Petroleum	1,106,561
NY	Petroleum	24,044,258
OH	Petroleum	1,390,649
PA	Petroleum	4,965,387
RI	Petroleum	55,814
VT	Petroleum	10,179
WI	Petroleum	724,230
WV	Petroleum	223,552
SUBTOTAL	Petroleum	53,403,149
CT	Other	10,356
IL	Other	0
IN	Other	425,310
MA	Other	0
ME	Other	0
MI	Other	0
MN	Other	45,959
NJ	Other	60,915
NY	Other	0
PA	Other	21,556
WI	Other	45,930
SUBTOTAL	Other	610,026

Appendix C - 3: Total Electrical Power Industry by Source for Northeast for 2005 by State – Natural Gas and Nuclear

CT	Natural Gas	8,863,687
DE	Natural Gas	1,590,761
IA	Natural Gas	2,480,842
IL	Natural Gas	7,116,309
IN	Natural Gas	3,623,916
MA	Natural Gas	20,276,566
MD	Natural Gas	1,873,659
ME	Natural Gas	8,398,454
MI	Natural Gas	13,631,871
MN	Natural Gas	2,743,986
MO	Natural Gas	3,865,467
NH	Natural Gas	6,784,735
NJ	Natural Gas	15,197,165
NY	Natural Gas	31,831,006
OH	Natural Gas	2,694,229
PA	Natural Gas	10,805,642
RI	Natural Gas	5,990,746
VT	Natural Gas	2,240
WI	Natural Gas	6,376,452
WV	Natural Gas	285,395
SUBTOTAL	Natural Gas	154,433,128
CT	Nuclear	15,562,122
IA	Nuclear	4,538,313
IL	Nuclear	93,263,001
MA	Nuclear	5,475,057
MD	Nuclear	14,703,221
MI	Nuclear	32,871,574
MN	Nuclear	12,835,219
MO	Nuclear	8,030,577
NH	Nuclear	9,455,885
NJ	Nuclear	31,391,685
NY	Nuclear	42,443,152
OH	Nuclear	14,802,733
PA	Nuclear	76,289,432
WI	Nuclear	9,920,991
SUBTOTAL	Nuclear	371,582,962

Appendix C - 4: Total Electrical Power Industry by Source for Northeast for 2005 by State – Hydroelectric Conventional and Pumped Storage

CT	Hydroelectric Conventional	478,199
IA	Hydroelectric Conventional	959,526
IL	Hydroelectric Conventional	129,037
IN	Hydroelectric Conventional	438,282
MA	Hydroelectric Conventional	1,041,950
MD	Hydroelectric Conventional	1,703,639
ME	Hydroelectric Conventional	4,090,926
MI	Hydroelectric Conventional	1,461,708
MN	Hydroelectric Conventional	774,729
MO	Hydroelectric Conventional	1,159,326
NH	Hydroelectric Conventional	1,064,180
NJ	Hydroelectric Conventional	31,113
NY	Hydroelectric Conventional	25,782,518
OH	Hydroelectric Conventional	515,744
PA	Hydroelectric Conventional	2,232,179
RI	Hydroelectric Conventional	6,734
VT	Hydroelectric Conventional	1,210,811
WV	Hydroelectric Conventional	1,447,566
SUBTOTAL	Hydroelectric Conventional	44,526,514
CT	Pumped Storage	-1,653
MA	Pumped Storage	-461,643
MI	Pumped Storage	-1,106,241
MO	Pumped Storage	85,932
NJ	Pumped Storage	-282,707
NY	Pumped Storage	-780,731
PA	Pumped Storage	-711,041
SUBTOTAL	Pumped Storage	-3,258,084
TOTAL	All Fuel Sources	1,565,033,485

Appendix D - 1 SimaPro 7 air emission inventory for 100% natural gas scenario

SimaPro 7.0	Inventory	Date:	6/26/2007	Time:	11:23:40 AM	
Project	NE/NC hardwood lumber LCI 100%NG					
Title:	Comparing 1 kg material 'Hardwood lumber, plane dry, NE/NC'					
Method:	EPS 2000 V2.02 / EPS					
Compartment:	Airborne emission					
Per sub-compartment:	No					
Default units:	Yes					
Indicator:	Inventory					
Relative mode:	Non					
No	Substance	Compartm	Unit	Hardwood lumber, plane dry, NE/NC		
1	Radioactive species, unspecified	Air	Bq	2184.618015		
2	Carbon dioxide, fossil	Air	kg	0.616493536		
3	Sulfur oxides	Air	kg	0.008033349		
4	Nitrogen oxides	Air	kg	0.002388521		
5	VOC, volatile organic compounds	Air	kg	0.002094355		
6	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	0.00199544		
7	Methane	Air	kg	0.001602491		
8	Particulates	Air	kg	0.001563429		
9	Carbon monoxide	Air	kg	0.00142075		
10	Particulates, unspecified	Air	kg	0.000152667		
11	Carbon dioxide, biogenic	Air	kg	0.000151681		
12	Particulates, < 10 um	Air	kg	8.84557E-05		
13	Hydrogen chloride	Air	kg	1.0198E-05		
14	Formaldehyde	Air	kg	6.20746E-06		
15	Organic substances, unspecified	Air	kg	3.74854E-06		
16	Aldehydes, unspecified	Air	kg	1.98838E-06		
17	Hydrogen fluoride	Air	kg	1.41384E-06		
18	Dinitrogen monoxide	Air	kg	1.17091E-06		
19	Ammonia	Air	kg	3.86807E-07		
20	Metals, unspecified	Air	kg	6.03006E-08		
21	Nickel	Air	kg	5.54111E-08		
22	Kerosene	Air	kg	5.46029E-08		
23	Selenium	Air	kg	1.54984E-08		
24	Manganese	Air	kg	1.53997E-08		
25	Methane, dichloro-, HCC-30	Air	kg	8.13509E-09		
26	Lead	Air	kg	7.78518E-09		
27	Chromium	Air	kg	7.77275E-09		
28	Phenol	Air	kg	6.61948E-09		
29	Arsenic	Air	kg	6.19349E-09		
30	Cobalt	Air	kg	4.82965E-09		
31	Mercury	Air	kg	4.28591E-09		
32	Methane, tetrachloro-, CFC-10	Air	kg	4.28163E-09		
33	Cadmium	Air	kg	3.93395E-09		
34	Chlorine	Air	kg	2.75863E-09		
35	Acrolein	Air	kg	2.03653E-09		
36	Benzene	Air	kg	2.01752E-09		
37	Ethene, tetrachloro-	Air	kg	1.95788E-09		
38	Antimony	Air	kg	1.93728E-09		
39	Ethene, trichloro-	Air	kg	1.92362E-09		
40	Beryllium	Air	kg	6.2236E-10		
41	N-Nitrodimethylamine	Air	kg	4.30274E-10		
42	Naphthalene	Air	kg	2.19736E-10		
43	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	kg	1.07846E-14		

Appendix D - 2 SimaPro 7 air emission inventory for 100% wood fuel scenario

SimaPro 7.0	Inventory	Date:	6/26/2007	Time:	11:32:15 AM	
Project	NE/NC hardwood lumber LCI 100% Wood Fuel					
Title:	Comparing 1 kg material 'Hardwood lumber, plane dry, NE/NC'					
Method:	EPS 2000 V2.02 / EPS					
Compartment:	Airborne emission					
Per sub-compartment:	No					
Default units:	Yes					
Indicator:	Inventory					
Relative mode:	Non					
No	Substance	Compartm	Unit	Hardwood lumber, plane dry, NE/NC		
1	Radioactive species, unspecified	Air	Bq	2480.881086		
2	Carbon dioxide, biogenic	Air	kg	0.916764915		
3	Carbon dioxide, fossil	Air	kg	0.193440829		
4	Carbon monoxide	Air	kg	0.006469087		
5	Particulates	Air	kg	0.002263727		
6	VOC, volatile organic compounds	Air	kg	0.002168417		
7	Nitrogen oxides	Air	kg	0.001773312		
8	Sulfur oxides	Air	kg	0.001318769		
9	Methane	Air	kg	0.00035507		
10	Potassium	Air	kg	0.000340488		
11	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	0.00019474		
12	Particulates, unspecified	Air	kg	0.000166328		
13	Particulates, < 10 um	Air	kg	0.000142576		
14	Organic substances, unspecified	Air	kg	7.34135E-05		
15	Phenol	Air	kg	1.74665E-05		
16	Hydrogen chloride	Air	kg	1.1738E-05		
17	Formaldehyde	Air	kg	1.05169E-05		
18	Sodium	Air	kg	7.85741E-06		
19	Manganese	Air	kg	3.94557E-06		
20	Chlorine	Air	kg	3.40732E-06		
21	Zinc	Air	kg	1.9207E-06		
22	Iron	Air	kg	1.9207E-06		
23	Barium	Air	kg	1.9207E-06		
24	Hydrogen fluoride	Air	kg	1.62971E-06		
25	Benzene	Air	kg	1.57361E-06		
26	Dinitrogen monoxide	Air	kg	1.34469E-06		
27	Acetaldehyde	Air	kg	1.30957E-06		
28	Naphthalene	Air	kg	1.04779E-06		
29	Aldehydes, unspecified	Air	kg	9.6674E-07		
30	Lead	Air	kg	5.31962E-07		
31	Ammonia	Air	kg	4.23243E-07		
32	Nickel	Air	kg	2.95067E-07		
33	Kerosene	Air	kg	6.30281E-08		
34	Arsenic	Air	kg	4.50171E-08		
35	Chromium	Air	kg	2.84007E-08		
36	Metals, unspecified	Air	kg	2.73285E-08		
37	Selenium	Air	kg	1.75525E-08		
38	Methane, dichloro-, HCC-30	Air	kg	9.32385E-09		
39	Mercury	Air	kg	4.80092E-09		
40	Cobalt	Air	kg	4.73879E-09		
41	Methane, tetrachloro-, CFC-10	Air	kg	4.6499E-09		
42	Cadmium	Air	kg	3.59251E-09		
43	Acrolein	Air	kg	2.34636E-09		
44	Ethene, tetrachloro-	Air	kg	2.24874E-09		
45	Ethene, trichloro-	Air	kg	2.21605E-09		
46	Antimony	Air	kg	1.94625E-09		
47	Beryllium	Air	kg	6.84039E-10		
48	N-Nitrodimethylamine	Air	kg	4.95387E-10		
49	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	kg	1.23874E-14		

Appendix D - 3 SimaPro 7 air emission inventory for original (base) scenario

SimaPro 7.0	Inventory	Date:	6/26/2007	Time:	11:47:34 AM	
Project	NE/NC hardwood lumber LCI					
Title:	Comparing 1 kg material 'Hardwood lumber, plane dry, NE/NC'					
Method:	EPS 2000 V2.02 / EPS					
Compartment:	Airborne emission					
Per sub-compartment:	No					
Default units:	Yes					
Indicator:	Inventory					
Relative mode:	Non					
No	Substance	Compartm	Unit	Hardwood lumber, plane dry, NE/NC		
1	Radioactive species, unspecified	Air	Bq	2383.834642		
2	Carbon dioxide, biogenic	Air	kg	0.763802298		
3	Carbon dioxide, fossil	Air	kg	0.247356253		
4	Carbon monoxide	Air	kg	0.005576446		
5	VOC, volatile organic compounds	Air	kg	0.002147404		
6	Particulates	Air	kg	0.002066475		
7	Sulfur oxides	Air	kg	0.002053754		
8	Nitrogen oxides	Air	kg	0.001826381		
9	Methane	Air	kg	0.000486235		
10	NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	0.000414094		
11	Potassium	Air	kg	0.000283669		
12	Particulates, unspecified	Air	kg	0.000161386		
13	Particulates, < 10 um	Air	kg	0.00013109		
14	Organic substances, unspecified	Air	kg	6.17533E-05		
15	Phenol	Air	kg	1.45528E-05		
16	Hydrogen chloride	Air	kg	1.12592E-05		
17	Formaldehyde	Air	kg	9.63353E-06		
18	Sodium	Air	kg	6.54621E-06		
19	Manganese	Air	kg	3.28977E-06		
20	Chlorine	Air	kg	2.83984E-06		
21	Zinc	Air	kg	1.60018E-06		
22	Iron	Air	kg	1.60018E-06		
23	Barium	Air	kg	1.60018E-06		
24	Hydrogen fluoride	Air	kg	1.56292E-06		
25	Benzene	Air	kg	1.31131E-06		
26	Dinitrogen monoxide	Air	kg	1.29013E-06		
27	Aldehydes, unspecified	Air	kg	1.28195E-06		
28	Acetaldehyde	Air	kg	1.09103E-06		
29	Naphthalene	Air	kg	8.7297E-07		
30	Lead	Air	kg	5.03097E-07		
31	Ammonia	Air	kg	4.27124E-07		
32	Nickel	Air	kg	2.54918E-07		
33	Kerosene	Air	kg	6.04242E-08		
34	Arsenic	Air	kg	3.85366E-08		
35	Metals, unspecified	Air	kg	3.14784E-08		
36	Chromium	Air	kg	2.63245E-08		
37	Selenium	Air	kg	1.68864E-08		
38	Methane, dichloro-, HCC-30	Air	kg	8.94797E-09		
39	Mercury	Air	kg	4.70678E-09		
40	Cobalt	Air	kg	4.68636E-09		
41	Methane, tetrachloro-, CFC-10	Air	kg	4.49163E-09		
42	Cadmium	Air	kg	3.89357E-09		
43	Acrolein	Air	kg	2.25029E-09		
44	Ethene, tetrachloro-	Air	kg	2.15741E-09		
45	Ethene, trichloro-	Air	kg	2.12534E-09		
46	Antimony	Air	kg	1.91548E-09		
47	Beryllium	Air	kg	7.26436E-10		
48	N-Nitrodimethylamine	Air	kg	4.75139E-10		
49	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Air	kg	1.18841E-14		