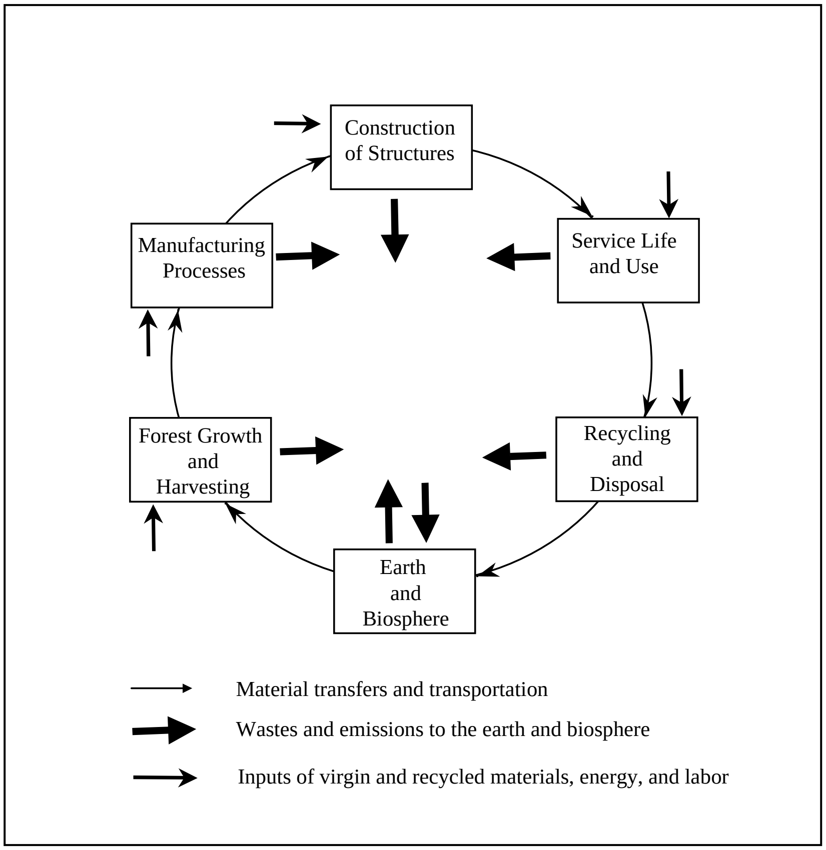
Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Construction



Phase II Research Report - on the research plan to develop environmental-performance measures for renewable building materials with alternatives for improved performance:

Extending the structural component supply regions to Northeast-Northcentral and Inland Northwest; assembly coverage to wall and floor components; product coverage to resins, medium density fiberboard, particleboard, and hardwood floors; and virtual building structures to west coast locations with seismic requirements

VOLUME 1: Executive Summary, Main Report and Summary Data Tables

January 2010 with supplements through February 2011

Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.)

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VOLUME LIST

Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Construction

Phase II Research Report: an Extension to the 2005 Phase I Research Report

Preface and Executive Summary

Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.)

This report is prepared with financial support from the USFS (JV11111137-084&094) and contributions from a number of private companies based on a research plan developed for the Department of Energy (DOE Agreement No. DE-FC07-96ID13437) as a part of the American Forest and Paper Association's Agenda 2020 priorities. Any opinions, findings, conclusions, or recommendation expressed in this publication are those of the authors and do not necessarily reflect the view of the financially contributing entities or participating institutions.

Preface

In 1998, the Consortium for Research on Renewable Industrial Materials (CORRIM), with the financial support of its research institutions and company members and a grant from the Department of Energy developed (1) a 22 module research plan to develop a life cycle inventory and analysis for wood used in U.S. construction, (2) a *Data, Standards and Procedures: Guideline for Life Cycle Inventories and Analysis*, and (3) an organizational structure to conduct the research plan and obtain thorough reviews of the data developed and the methods used. A Phase I research plan was designed to pilot-test the collection and analysis of the data for the first 5 modules. The Phase II research provided in this report focuses on geographic, product, and building structure extensions. The Phase I&II research develops a database and modeling capability to adequately describe the environmental performance of most wood-based building materials and many of their uses in the US. The research develops primary life cycle environmental performance data for and analyzes key wood materials such as lumber, plywood, composite panels, other structural wood derived products, high volume non-structural products such as MDF, particleboard, resins and hardwood floors. It also provides environmental and selected economic data on life-cycle stages from planting and growing the renewable raw material, manufacture of products, through to the design and construction of subassemblies and buildings. The impacts of occupation and building use through final demolition are available in the Phase I Report at, http://www.corrim.org/reports/2006/final_phase_1/index.htm.

The collection of all input and output data for each stage of processing is referred to as the Life Cycle Inventory (LCI). The data and subsequent analysis follows consistent definitions and collection procedures for the development of LCI profiles for each product and region and to facilitate the integration of results across the full life cycle of material processing and use in order to address environmental performance questions. The ultimate use of LCI information is to analyze it for risk implications on human or ecological health and how the risk can be lowered resulting in improved environmental performance. This assessment process is referred to as Life Cycle Assessment (LCA).

The Phase I report provided both a pilot project for testing and review of research methods and partial product and regional coverage for 5 of the 22 modules as described in the original research plan developed for the Department of Energy under Agenda 2020 priorities for pre-competitive research needs. Phase II extends the coverage to 11 of the modules in the research plan while also providing more complete geographic coverage. The coverage of the Phase I & II research plans is summarized in Table 1. A Phase III research plan has been initiated to cover the biofuel collection and processing module described in the initial research plan. Research modules that have not yet been funded include more comprehensive substitution of products in both structural and interior applications, alternative building designs and non-building uses ranging from furniture to bridges and docks.

Table 1. Summary of Phase I & II Research Plan Coverage

Subject	**Phase I**	**Phase II**
Study Period	2000 – 2004	2005 - 2009
Forest Resources Module	Southeast (SE), Pacific Northwest (PNW)	Northeast-Northcentral (NE-NC), Inland Northwest (INW)
Houses (LCA)	Atlanta, Minneapolis	California/Southwest, Seattle/Northwest (seismic codes)
Wood products	Lumber (regional), Plywood, Oriented strand board (OSB), Laminated veneer lumber (LVL), glulam, I-joist	Lumber (softwood & hardwood), particleboard, medium density fiberboard (MDF), resins, hardwood flooring
Non-wood framing	Concrete, steel frame	Concrete, steel frame
Housing design	Residential – single dwelling	Residential single, multi-family, low rise commercial and subassemblies
Forest Management	Fertilization, thinning	Partial cutting, Fire risk reduction, Northeast hardwoods

The USFS Forest Products Laboratory, 15 research institutions and about 12 companies have contributed financial support for the research.

The report is organized as follows: Major points are introduced in the Executive Summary. Readers are directed to the Phase I Final Report, Section 1 for the background, mission, organization of effort and objectives although key sections of the Phase I Report are repeated here with some updating to reduce the need for cross-referencing. The Phase I Report also provides details on the review process including peer reviews by noted international experts to ascertain conformity with the ISO 14040 series, the international standards for LCI/LCA. Given the thorough mythological review completed in Phase I, and the extensive review by LCI experienced non-authors from CORRIM institutions with minimal changes in methods, the more conventional double blind peer review process for journal publication was adopted for Phase II. The full Phase I report was summarized by 12 articles in a special issue of Wood and Fiber Science, the Journal of the Society of Wood Science and Technology: Special Issue: CORRIM Reports on Environmental Performance of Wood Building Materials, Volume 37, December 2005 (ISSN 0735-6161). The new findings from this Phase II report have been peer reviewed and published in Wood and Fiber Science Volume 43 CORRIM Speical Issue, March 2010

Section 1 of this Phase II Report provides an introduction to the objectives and method similar to that provided in the Phase I report although updated to include the scope of the Phase II research. Section 2 reviews the framework for developing LCI data and life cycle assessments comparison.

Section 3 provides a general description of what was accomplished in Phase II to supplement the findings in the Phase I reports. Section 4 provides a summary of significant differences in the cradle to production gate LCIs for all Phase I and II wood products. Cradle to production gate LCI tables for structural products from both Phase I and II are provided in Appendix A. Section 5 summarizes some of the more obvious opportunities to improve environmental performance by looking at the impact of each component within subassemblies. Section 6 summarizes the impact of west coast seismic requirements on LCA performance. Section 7 provides a summary of the use of LCI data for tracking carbon from the forest through multiple product uses with comparisons across several regions and owner specific management objectives. Section 8 provides a summary list of significant opportunities to reduce environmental burdens based on the Phase I and II reports.

The findings for each stage of processing are reported in 11 modules (Modules A-K). Modules A-E & L are stand alone LCI reports for forest resources, and primary wood products including hardwood and softwood lumber and one secondary product, hardwood flooring. Modules F-H are stand alone LCI reports for particleboard, medium density fiberboard, and resins with the feedstock inputs derived from the Primary Product Reports. Module I provides an LCI/LCA analysis of structural wall and floor subassemblies and the impact of critical component alternatives. Module J extends the construction design for residential building shells and their corresponding bill of materials from the Phase I virtual houses for Atlanta as a warm climate and Minneapolis as a cold climate to West Coast Seismic Codes for both north (Seattle) and south (Los Angeles) with their much more demanding seismic requirements. CORRIM's research has largely been focused on the commercial forests that support sustainable log production and the uses of wood once it leaves the forest. For Module K, the impact of federal forests, although not being managed for commercial objectives, is critical given their substantial acreage and their high and increasing risk of fire. This module extends the data developed for the Inland Northwest Forest Resources to provide carbon tracking across the landscape that includes the impacts of expected wildfire rates and identifies how restoration of overly dense forests using fire risk reduction treatments can provide an important ecosystem and carbon benefit.

Overall, this report attempts to provide a more complete record of the research data for open access and to complement the more abbreviated articles provided in peer reviewed journals, including both more detailed LCI data and analytical nuances.

Executive Summary

Background and Study Objectives:

The Consortium for Research on Renewable Industrial Materials (CORRIM) is a non-profit organization supported by 15 research institutions for the purpose of updating and expanding a 1976 landmark study by the National Academy of Science on the energy implications of producing and using renewable building materials. We use the same CORRIM acronym as the 1976 study, which was managed by a committee of scientists.

We address an expanding list of environmental-performance issues that has gained considerable attention since the 1976 CORRIM study. A 1000 page phase I Research Report was published in 2004 (http://www.corrim.org/reports/2006/final_phase_1/index.htm) and a special edition of Wood and Fiber Science (Vol 37, Dec. 05, 155 pages) provided a journal version of the full report along with a summary article in the Forest Products Journal (June 2004) http://www.corrim.org/reports/pdfs/FPJ_Sept2004.pdf. The Phase I Report provided LCI data on every stage of processing from forest management in the Pacific Northwest (PNW) and Southeast (SE) supply regions to building construction and demolition of structures in a warm climate (Atlanta) and a cold climate (Minneapolis). This Phase II Report extends the geographic coverage from the PNW and SE supply regions to Northeast-Northcental (NE-NC) both hardwoods and softwoods and Inland Northwest (INW) softwoods. It extends the product coverage from softwood lumber, plywood, oriented strandboard, glulam beams and laminated veneer lumber to include hardwood lumber and flooring, medium density fiberboard, particleboard and resins. Many environmental improvement opportunities are identified by examining the impacts of using different components in floor and wall assemblies as well as increased use of biofuels in processing mills. These reports develop a comprehensive life-cycle database and performance measures, which can be used to formulate public policy affecting renewable materials industries. The database is useful for companies to develop strategic investment plans that could improve their environmental performance and is incorporated in the National Renewable Energy Laboratory USLCI database (NREL 2003, NREL, 2004) covering both wood based and non-wood based materials for access by LCI/LCA practitioners.

The Overall Project Study's Objectives Are:

To create a consistent database of environmental performance measures associated with the production, use, maintenance, re-use, and disposal of alternative wood and non-wood materials used in light construction, i.e., from forest resource regeneration or mineral extraction to end use and disposal, thereby covering the full product life-cycle from “cradle to grave.”

To develop an analytical framework for evaluating life-cycle environmental and economic impacts for alternative building materials in competing or complementary applications so that decision-makers can make consistent and systematic comparisons of options for improving environmental performance.

To make source data available for many users, including resource managers and product manufacturers, architects and engineers, environmental protection and energy conservation analysts, and global environmental policy and trade specialists.

To manage an organizational framework to obtain the best scientific information available as well as provide for effective and constructive peer review. To ensure that the databases established in this report were recognized and accepted, strict international protocols conforming to ISO standards were followed throughout the planning, data collection, analysis, reporting and review process.

Both the Phase I and II Reports are intended to be used as a reference source that contains the databases and analytical framework for those interested in the LCI and LCA for environmental performance of building materials. The intent is to provide the reader with an explanation of the data and methods used in LCI and LCA. In various places we have demonstrated the use of such data using the LCA approach such as understanding the life cycle of carbon from the forests through product uses and their impact of offsetting carbon emissions from fossil intensive products. Many shorter papers can and have been written on impact assessment based on the information contained in these reports, largely focused on environmental improvements. The report demonstrates a number of sensitivity analyses through the comparisons of alternative scenarios.

Primary and Secondary Data Sources:

Primary data on all inputs and outputs associated with the production of all wood products were collected through surveys of a range of mill types within specific processing regions. Growth and yield models representing conditions in the NE-NC and INW growing regions and recent studies of harvesting activities were used to gather forest regeneration, growth and log production data. The integration of growth and yield models and harvesting methods stratified across a landscape provides the data equivalence of primary survey data on processing mills for forest resources. We conducted analyses of mass and energy balances for each product processing stage in order to provide a validity check on the data quality. We also compared different mills in the same region and analyzed the differences across regions.

The data collected were used to construct LCIs for the various wood products i.e. measures of all inputs and outputs across each stage of processing using SimaPro software. We prepared LCIs based on internal processing emissions as well as tracing the impacts back to include the burdens generated by the primary energy producers that supply the purchased energy. These LCIs were incorporated into the ATHENA™ Environmental Impact Estimator model (EIE). The EIE model provides LCI measures and LCA performance indices for a completed building based on the bill of materials developed for the US house designs using the LCI data that CORRIM has developed for each US wood product. The EIE also contains LCIs for non-wood materials used in construction that are generally available in the US LCI database managed by National Renewable Energy Laboratory (NREL). The ATHENA™ Institute, a Canadian research institute and cooperator on the project, then proceeded to analyze the environmental impacts resulting from the architectural designs for the representative residential structures and corresponding bill of materials.

An objective of the research is to analyze the product life-cycle from planting and growing the renewable raw material to final demolition of a building. The environmental burdens from the production processes used to produce building materials were allocated according to the mass of materials used in each unit process for producing products and then for the mass of products used in building construction. Allocation of burdens at the unit process level results in the energy for drying being charged only to products that were dried. Since drying energy is the dominant use of energy in the production of wood, there is relatively little energy or energy related burdens assigned to co-products. Burdens were allocated to co-products such as the chips used to make paper based on their mass share for the stage of processing where they were generated. Similarly, the burden accumulated from transportation, processing energy, and construction energy was allocated to the building according to the mass of materials used in building construction. The environmental impacts from energy uses are derived from national or regional grids of purchased electrical energy and fossil fuels. Thus the environmental burdens derived from energy consumption are allocated according to the specific type of energy consumed (11 types) and its place of origin (raw material and manufacturing producing regions and construction regions). Other users of the data may rely on national and even international energy sources producing different burdens reflecting broader averages than is appropriate for wood products that demonstrate regional differences. It is important to note that this process for allocating burdens is product and regionally specific and not biased by industry and national averages that may be available in national industrial databases. Average burdens can be very misleading for select products.

An important change in the Phase II research protocol for product LCIs was to include the carbon stored in products for the life of the house as an offset to the greenhouse gas emissions from processing. With sustainably managed forests, the increased carbon the forest absorbs through new growth does not remain in the forest which remains carbon neutral but is exported out of the forest and stored with the products. While accounted for as a separate carbon pool in the Phase I research plan, third party data users frequently omitted the impact of the carbon in products. Linking the carbon in the product LCI acts as an offset to product processing emissions for more comprehensive accounting and greater transparency.

In this study, many emissions are reported for each stage of production (extraction, manufacturing, transportation) with the most important being carried forward to the building construction stage. Vital stand structure measures of the forestland environment are also tracked to describe their effects on water, habitat, carbon and biodiversity, several of which require landscape-wide measures to be useful. In Phase I, an analysis of the impact of alternatives on habitat/biodiversity did not produce substantially different impacts across active management alternatives. In the Phase II analysis the impact of management on fire was considered to be the dominant ecosystem concern and was addressed for the Inland Northwest forest including Federal Forests where the "Healthy Forest Initiative" objectives of improving their health will alter environmental impacts.

These complex arrays of environmental outputs for the construction of a residential building are reduced to environmental performance indices organized to provide a life cycle assessment of human and ecosystem health impacts as a simplified communication of findings. However, the science behind best weighting schemes to represent aggregate environmental risk indices for water, air, solid waste, global warming potential, and forest health is still evolving, and in certain cases may be controversial and beyond the scope of this report.

Environmental Performance Index Comparisons for Residential Building Construction with the Impact of Carbon Stored in Products:

The ATHENA™ Institute derived indices for water and air emissions, solid waste, and global warming potential to reduce the complexity associated with the large number of individual emissions. Indices used to measure the impacts from use, maintenance and disposal of a building, as well as forest biodiversity and the carbon stored in the forest are developed separately since these effects occur over a long period of time in contrast to the narrow time frame associated with impacts from extraction to construction. Table ES-1 as updated from the Phase I report presents the indexes associated with production stages. For Global Warming Potential the table provides impacts based on processing energy as was the protocol for the Phase I research plan and a separate calculation including the impact of carbon stored in products, as the protocol adopted for the Phase II research. With two exceptions, all of the construction index measures indicate significantly lower environmental risk for the wood framing design in Atlanta and Minneapolis compared to non-wood framing alternatives. The exceptions are that the steel design in Minneapolis produces less solid waste than the wood design although the difference is insignificant and there is no significant difference in the water pollution index for the Atlanta designs.

The impacts on carbon however are especially noteworthy given the increased attention being focused on global warming and national objectives to substantially reduce carbon emissions. Recognition that the carbon stored in wood products offsets many of the emissions from other products substantially alters the comparisons. Despite the small total mass difference resulting from substituting steel or concrete framing for wood, the Global Warming Potential (GWP given in CO_2 equivalent of greenhouse gas emissions of CO_2, methane and nitrous oxide) from the steel-framed house are 26% greater than the house with wood walls and floors, without considering the carbon stored in wood products. This becomes a 120% difference when the carbon stored in the wood products for the life of the house is included. Emissions from the completed, concrete wall-framed house are 31% greater than the wood wall house without considering the carbon stored in wood products, and 156% greater when these carbon stores are included in the calculation. As a major opportunity for improvement, a design change to eliminate the concrete basement in the Minneapolis house and the concrete slab floor in the Atlanta house would substantially alter the carbon footprint for the life of each house and may be sufficient to offset the carbon emissions from the remaining non-wood products being used, however the functional use may also be affected.

Table ES1. Environmental Performance Indices for Residential Construction.

Minneapolis design	Wood	Steel	Difference	Other Design vs. Wood (% change)
Embodied Energy (GJ)	651	764	113	17%
Global Warming Potential from processing (CO_2 kg)	37,047	46,826	9,779	26%
Global Warming Potential net of carbon stored in products (CO_2 kg)	16,561	36,428	19,867	120%
Air Emission Index (index scale)	8,566	9,729	1,163	14%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	-125	-0.9%
Atlanta design	**Wood**	**Concrete**	**Difference**	**Other Design vs. Wood (% change)**
Embodied Energy (GJ)	398	461	63	16%
Global Warming Potential from processing (CO_2 kg)	21,367	28,004	6,637	31%
Global Warming Potential net of carbon stored in products (CO_2 kg)	5,898	15,090	9,192	156%
Air Emission Index (index scale)	4,893	6,007	1,114	23%
Water Emission Index (index scale)	7	7	0	0%
Solid Waste (total kg)	7,442	11,269	3,827	51%

The primary difference in materials between the Minneapolis wood and steel house is the substitution of 6,000 kg of steel for wood in the floors and walls. Both designs share the same basement and roof elements with the total weight of all structural materials approaching 100,000 kg. The substitution of 6% of the materials by weight results in a substantially higher percentage increase in all of the environmental performance indices except solid waste, which is essentially unchanged.

For the Atlanta structure, the major difference between the wood and concrete design is the substitution of 8,000 kg of concrete (2,000 kg of limestone plus rebar and aggregate material) for 2,000 kg of wood in the exterior wall structure as both designs use similar concrete floors and wood roofs. The substitution of 8% of the materials by weight results in a substantial higher percentage increase in all of the environmental performance indices except water, which is essentially unchanged.

The Impact of Seismic Standards:

Considerable effort went into ensuring that these alternative structural material residential designs (wood, steel and concrete) were functionally equivalent and relevant to their regional locations and building codes. To expand the applicability of the Phase I research and alternative material design work to other areas of the country, in this report (Module J) Los Angeles (LA) and Seattle were selected for their different climates and seismic standards. Seismic risks result in the use of a number of additional structural materials and systems to satisfy local codes. As a first step we used the basic Minneapolis house design absent the basement in favor of a crawl space, which is more common in the west, and compared the impact of a Seattle and LA seismic code to the same house with each built in Minneapolis to eliminate logistical differences thereby focusing only on the impact of seismic requirements. Future work will cover the impacts of different logistics and material sourcing for the Seattle and LA locations.

Seismic codes like other building codes are locally controlled and subject to change but the relative magnitudes of the impacts on environmental burdens trace directly from the objectives of the codes to withstand earthquakes with minimal damage. Seismic base shear calculations for both Seattle and LA were calculated using the 2003 International Building Code (IBC 2003) and ASCE-7-02 Minimum Design Loads for Buildings as referenced by IBC 2003. The requirements vary depending on the height and mass of a building the structural framing configuration, soil conditions and proximity to active faults.

The impact of the materials and design changes on the structural frame (absent insulation and interior coverings) calculated in terms of embodied primary energy, global warming potential (GWP), air and water pollution and solid waste effects resulted in significant increases in the environmental footprint of residential structures, ranging from an increase of 60 to 100% for energy, GWP and air pollution. The absolute value increases are larger for the steel frame than wood frame but smaller in percentage terms given the higher burdens for steel before including seismic requirements. The increased burdens from meeting the seismic codes are substantial with the increase for a wood design slightly larger than the impact of substituting a steel frame for a wood frame without an increase in seismic requirements. Heavier structures are likely to require more fastener-like materials for increased strength producing somewhat larger impacts. A better understanding of these impacts should motivate design and material use changes as opportunities to lower the environmental impacts in new residential structures.

The Impact of Product Selection, Processing Method and Design:

While it is evident from the life cycle analysis of house designs that wood framing generally produces lower environmental burdens than concrete or steel alternatives just how to go about selecting best products or process changes (such as biofuel drying) is difficult. Lippke and Edmonds (2006) demonstrated several alternatives for reducing environmental burdens by simple product selection alternatives in walls and floor assemblies while also altering the energy production process for wood drying to be more dependent on wood residuals. This report (Module I) provides additional detail on the impact of burdens at the component level resulting from substituting steel studs or concrete block for wood studs in conjunction with OSB or plywood sheathing and wood or vinyl cladding in walls, and steel joists or concrete slab for wood floors. By analyzing the impacts at the level of components and those components most critical in structural assemblies, strategies for environmental improvement become more obvious.

As noted in Figure ES1, the wood floor-joist ***components*** that are used in the construction of floors (dimension wood joist {Dim-Joist} and Engineered Wood I-Joists {EWP I-Joist} both store carbon (negative emissions) as their emissions from processing are more than offset by the carbon removed from a sustainably managed carbon neutral forest that is then stored in the products. In contrast, the non-wood Concrete Slab and Steel Joists result in substantial carbon emissions (2-4 kgCO_2/sq ft of floor). Adding a wood covering (plywood {Ply} or oriented strandboard {OSB}) to steel joists for a ***floor-assembly*** does not offset the emissions from the heavy gauge steel that is used in flooring. EWP I-joists with wood covering store less carbon than dimension joists because they use less fiber but all combinations of wood joist and wood covering store substantial amounts of carbon compared to non-wood joists and floor covering which result in significant emissions.

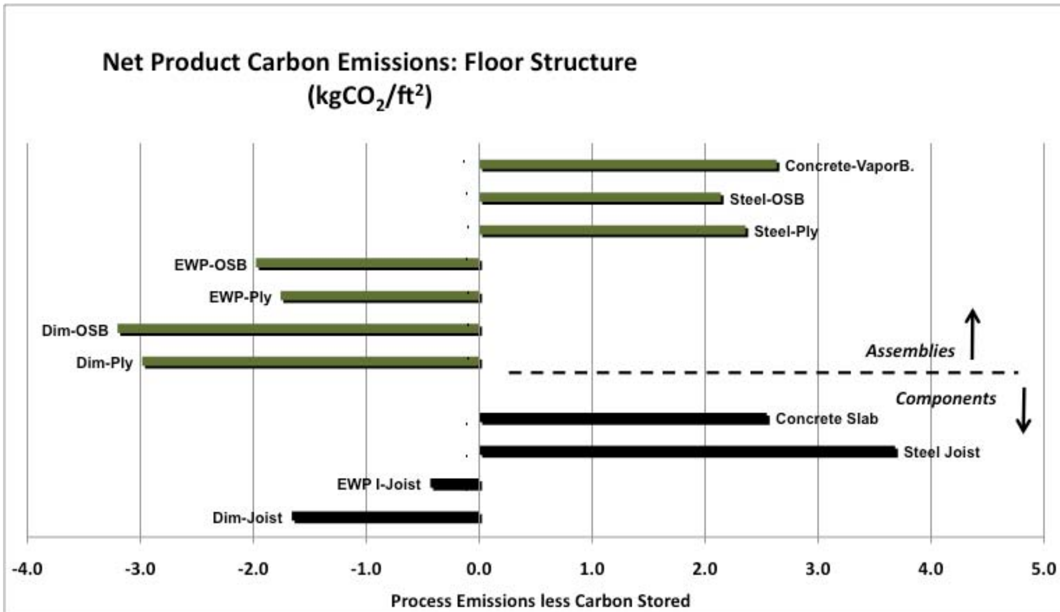

Figure ES1. Process Emissions less Carbon Stored in Floor Structure Components and Assemblies
(source: Module I in this report)

The EWP I-joist with an OSB cover is substantially better than a concrete slab reducing GWP emissions by 3 kg per sq. ft. of floor. Another measure of interest is the emission reduction relative to the fiber used as an efficiency of substitution measure. The EWP I-joist reduces CO_2 emissions by 4.6 kg per kg (dry weight) of wood used. The comparison with steel joists and OSB cover reduces emissions by 9.8 kg per sq. ft., more than twice as effective as the substitution for a concrete floor largely because steel joists must be heavy gauge to minimize floor bounce resulting in substantial processing emissions, a relatively poor application for steel. But since the steel floor also uses wood in the floor cover as a partial carbon offset it is less fiber efficient reducing emissions to 4.2 kg per kg of wood used, slightly less than by displacing concrete flooring. If there is an adequate supply of wood, greater use of wood will improve the carbon footprint in structures the most. If not, efficient use of fiber becomes important.

While displacing steel in floors by wood is more effective than displacing concrete these findings cannot be generalized to wall assemblies. As noted in Figure ES2, the wood-wall ***components*** (kiln dried stud {KDStud}, Plywood, OSB, biofuel dried plywood {BioDryPly}) all store carbon more than offsetting their processing emissions, and some ***wall assemblies*** use sufficient amounts of wood to more than offset the emissions of some non-wood components such as the emissions from the use of vinyl cladding. As a component, concrete block substitutes not only for wood studs, but also the wood sheathing and with the addition of a stucco cladding for any wood or vinyl cladding used with wood framed walls. The best configurations use wood products with biofuel used for drying. The assembly made of biofuel-dried-studs, biofuel-dried-plywood in both sheathing and cladding stores the most net carbon with the use of OSB sheathing almost as good.

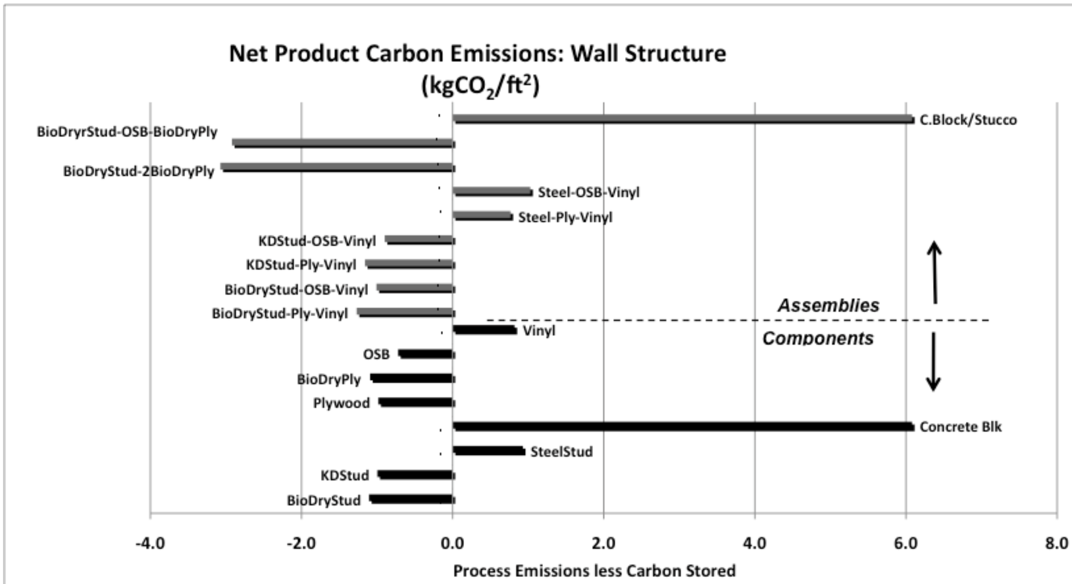

Figure ES2. Process Emissions less Carbon Stored for Wall Components and Assemblies (source: Module I this report)

Construction of a wall using biofuel dried studs and biofuel dried plywood for sheathing and cladding, reduces GWP by over 2.2 kg CO_2 eq. per sq. ft. of wall compared to the more conventional kiln dried wood stud using OSB sheathing and vinyl siding (Figure ES2). This substitution comparison had a fiber efficiency of 2.1 kg CO_2 eq. reduction per 1 kg of fiber used (top bars).

The benefit of this within wood substitution is almost the same as replacing a conventional steel wall assembly with a conventional wood assembly, which involves no increased use of biofuel in drying. By , increasing the use of biofuel and substituting for a steel framed wall assembly, GWP emissions are reduced by 4.1 kg CO_2 eq. per sq. ft. of wall with a fiber substitution efficiency of 2.7 kg CO_2 eq. per kg of wood fiber used.

Using the wood designs compared to a concrete and stucco wall result in GWP reductions of 7-9 kg CO_2 eq. per sq. ft. of wall or almost 3.5 kg CO_2 eq. per 1 kg use of fiber. While the wood is more effective at displacing the emissions from steel in floors and concrete in walls the displacement of emissions per unit of wood fiber used is not as different. The use of more fiber is a substantial part of the opportunity for improvements but may not provide the high leverage that is provided by critical component comparisons such as steel joists vs. EWP I-joist. Using more fiber as biofuel in products helps to reduce the GWP in structural assemblies by reducing fossil fuel emissions in processing but will not likely be as efficient as using fiber for structural components. It still may be the best use of low quality fiber not suitable for engineering into structural components. However, different components do perform better in different applications and these differences are not generally identified or valued in current market exchanges.

This sampling of materials and designs is not exhaustive but suggests many design, product and process changes that can improve environmental performance of buildings. The most obvious include (1) using a renewable wood resource instead of a fossil intensive resource and especially where the substitution advantage is large, (2) using biofuels to reduce the fossil fuel use in manufacturing wood, (3) using resource efficient materials pre-cut to length or pre-assembled units and (4) using recycled materials that require less energy. The results also suggest the potential for many future improvements in the design of components that can displace more energy intensive components and the design of new pre-assembled units that can gain several of these advantages at once.

Cradle to Production Gate Burdens:

The cradle-to-gate stages of processing include forest management and harvesting, transportation, and product manufacturing. The product manufacturing stage consumed the dominant share of energy representing 88% - 93% of the total. Energy for requirements for forest management and harvesting were low (4-5%) with the higher impacts resulting from areas using the most fertilization. Transportation energy use was also low, about 3-7% of total.

Total energy consumption for softwood lumber manufacturing (3,850-4,023 MJ/m^3) was about half of that required for hardwood lumber (6,844) and hardwood flooring (7,315). The use of wood biomass as the primary energy source for manufacturing greatly reduced the environmental burdens by offsetting the demand for fossil fuels. Bioenergy made up as little as 30% of total energy for INW softwood lumber production and as much as 71% for SE softwood lumber production. Natural gas provided as much as 47 % of total energy for INW softwood lumber while 4% natural gas and 4% was used softwood lumber in the NE-NC regions. The NE-NC region had the highest usage of coal and crude primarily for electricity generation. Products made with resins generally required more energy. SE OSB (11000 MJ/m^3) required almost twice as much energy as SE Plywood (5600) and with a much lower share of bioenergy (45% for plywood, 35% for OSB, compared to 71% for lumber). Not shown are the benefits from material use efficiency as OSB feedstock is sourced from otherwise underutilized forest resources.

The growing importance of carbon emissions provides a comparative advantage for wood products since the carbon stored in the products was removed from the atmosphere (a negative emission) and more than offsets other wood processing emissions.

Fire Impacts on Inland Forests

Forest inventory and harvest data from life cycle inventory (LCI) and life cycle assessment (LCA) for the forest resources of the INW region covering Idaho, Montana and eastern Washington were used to estimate the impacts of managements action on the full suite of carbon accounts that can accrue from forest management. The carbon accounts include the forest, wood products, the benefit gained from using wood products as substitutes for alternative products that are fossil fuel intensive to produce, and the displacement value of using woody biomass as an energy feedstock to replace fossil fuel. A landscape level assessment of projected carbon storage by owner group shows that by 100 years, management on State and Private forests can sequester or avoid emissions equal to 294 t/ha of carbon, which equals over 1.9 billion t of carbon across 6.5 million ha. Seventy nine percent of the carbon accumulates beyond current forest carbon inventories.

Fire rates have increased substantially on National Forests in recent years. On National Forests carbon sequestration and avoided emissions are 152 t/ha over 11 million ha of unreserved forests equals 1.4 billion t of carbon under predictions for a doubling of the 20^{th} century fire rate. The carbon storage in buildings and the benefits of substitution for fossil intensive products therein override the potential gains of attempting to leave high carbon stocks stored in the forest in this region where disturbance from fire and insect outbreaks dominates the forests' ability to sequester carbon.

Federal thinning treatments designed to reduce the risk of fire while at the same time retaining much of the large tree overstory to emulate pre-fire suppression forest structure can increase total carbon stores modestly but is largely constrained by the limited volume of removals from the larger trees that would substitute for fossil intensive structural products.

Environmental Improvement Opportunities:

The report indentifies many opportunities where environmental improvement opportunities would appear to be attractive and worth pursuing.

- Redesign of the house to use less fossil intensive products.
- Redesign of the house to reduce energy use (both active and passive).
- Revising building codes to reduce excessive use of wood, steel and concrete.
- Greater use of low valued wood fiber for biofuel (e.g., forest residuals, thinnings).
- Greater use of engineered products producing higher valued products from less desirable species.
- Improved process efficiencies such as the boiler or dryer (including air drying).
- Environmental pollution control improvements evaluated using LCI/LCA.
- More intensive forest management.
- Managing forests to reduce fire risk and increase resilience to climate change.
- Recycling demolition wastes including initial designs that motivate recycling.
- Increased product durability (given the already long expected life of a house, from 75-100 years, this applies primarily to moisture/weather exposed areas).
- Using more wood to meet seismic standards.
- Recognition that life cycle analysis is essential to measure improvement across all stages of processing as tradeoffs exist across the system, and that policy or investment decisions focusing on only one stage of processing or carbon pool may be counterproductive.
- Product development focused on reducing the environmental footprint along with product life.

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List of Modules and Database Addendums

Module reports by different authors were managed to conform to CORRIM Research Guidelines using SimaPro software to produce two LCI databases, one reflecting only internal manufacturing processes, and a second relying on external databases such as the impacts from the purchased energy grid to capture the burdens associated with external purchases. These Database Addendums document changes to the CORRIM SimaPro module output as a result of the review process for providing the data to NREL for inclusion in and conformity to the U.S. LCI database. Individual addendum reports may reflect actual changes to the original data as determined by the review process and agreed to by CORRIM's LCA integration consultant. Each addendum lists the specific changes that were made as well as the more general changes such as use of different databases for purchased materials for the U.S. LCI database. The more general changes include: Flow names not fitting U.S. LCI database nomenclature; unit processes connecting to the FAL database were modified to use the U.S. LCI data instead, unit processes were renormalized to produce “one unit” of product (rather than to represent the final amount needed to produce “one unit” of a downstream final product); final "waste flows" were converted to "waste management flows"; and measurement units were converted to use U.S. LCI database units.

Module A: Life Cycle Inventory (LCI) of Inland Northwest (INW) and Northeast-Northcentral (NE-NC) Forest Resources
By Leonard Johnson, Elaine Oneil, Bruce Lippke, Jim McCarter, Marc McDill, Paul Roth, James Finley with harvesting system data provided by Joe McNeel and Jingxin Wang

Module B: LCI of INW Softwood Lumber Manufacturing
By Francis Wagner and Maureen Puettmann

Module C: LCI of NE-NC Hardwood Lumber Manufacturing
By Richard Bergman and Scott Bowe

Module D: LCI of NE-NC Softwood Lumber Manufacturing
By Richard Bergman and Scott Bowe

Module E: LCI of NE-NC Hardwood Flooring Manufacturing
By Steve Hubbard and Scott Bowe

Module F: Cradle to Gate LCI of Medium Density Fiberboard (MDF) Manufacturing
By Jim Wilson

Module G: Cradle to Gate LCI of US Medium Density Particleboard Manufacturing
By Jim Wilson

Module H: Cradle to Gate LCI of US Wood Industry Resin Manufacturing
By Jim Wilson

Module I: Life-Cycle Assessments (LCA) of Subassemblies Evaluated at the Component Level
By Bruce Lippke, Lucy Edmonds

Module J: LCA Impacts from West Coast Seismic Codes
By Jamie Meil, Mark Lucuik

1.0 Introduction

1.1 Background

The motivation for developing comprehensive life cycle inventory (LCI) data for all inputs and outputs of every wood product stage of processing originates from the increasingly intense public interest and debate regarding environmental impacts and sustainability of building products manufacture and use, and, in particular, the intense concerns about forest management and the flows of products that originate from forests. This Phase II Research Report extends the findings in a Phase I report that began in 2000 with interim results including reviews published in 2002, a final research report published in 2004 followed by reviews and journal articles published in 2005. The findings in these reports substantially expand our understanding of the environmental consequences of changes in forest management, product manufacturing, consumption, and disposal for which there was previously no definitive data. CORRIM's Phase I and II Research Reports provide a comprehensive updating of a pioneering report published in 1976 by a Committee on Renewable Resources for Industrial Materials (CORRIM) under the auspices of the National Research Council (1976). That landmark study, now referred to as CORRIM I, has been thoroughly updated by the revitalized consortium referred to as CORRIM II, the Consortium for Research on Renewable Industrial Materials. A summary of significant changes in performance since the original CORRIM study are available in Lippke et al (2004) and Meil et al (2007). The intent in establishing CORRIM II was to develop:

- A consistent database to evaluate the environmental performance of wood and alternative materials from resource regeneration or extraction to end use and disposal, i.e. from "cradle to grave" (Figure 1.1).
- A framework for evaluating life-cycle environmental and economic impacts.
- Source data for many users, including resource managers, manufacturers, architects, engineers, environmental protection and energy analysts, and policy specialists.
- An organizational framework to obtain the best science and peer review.

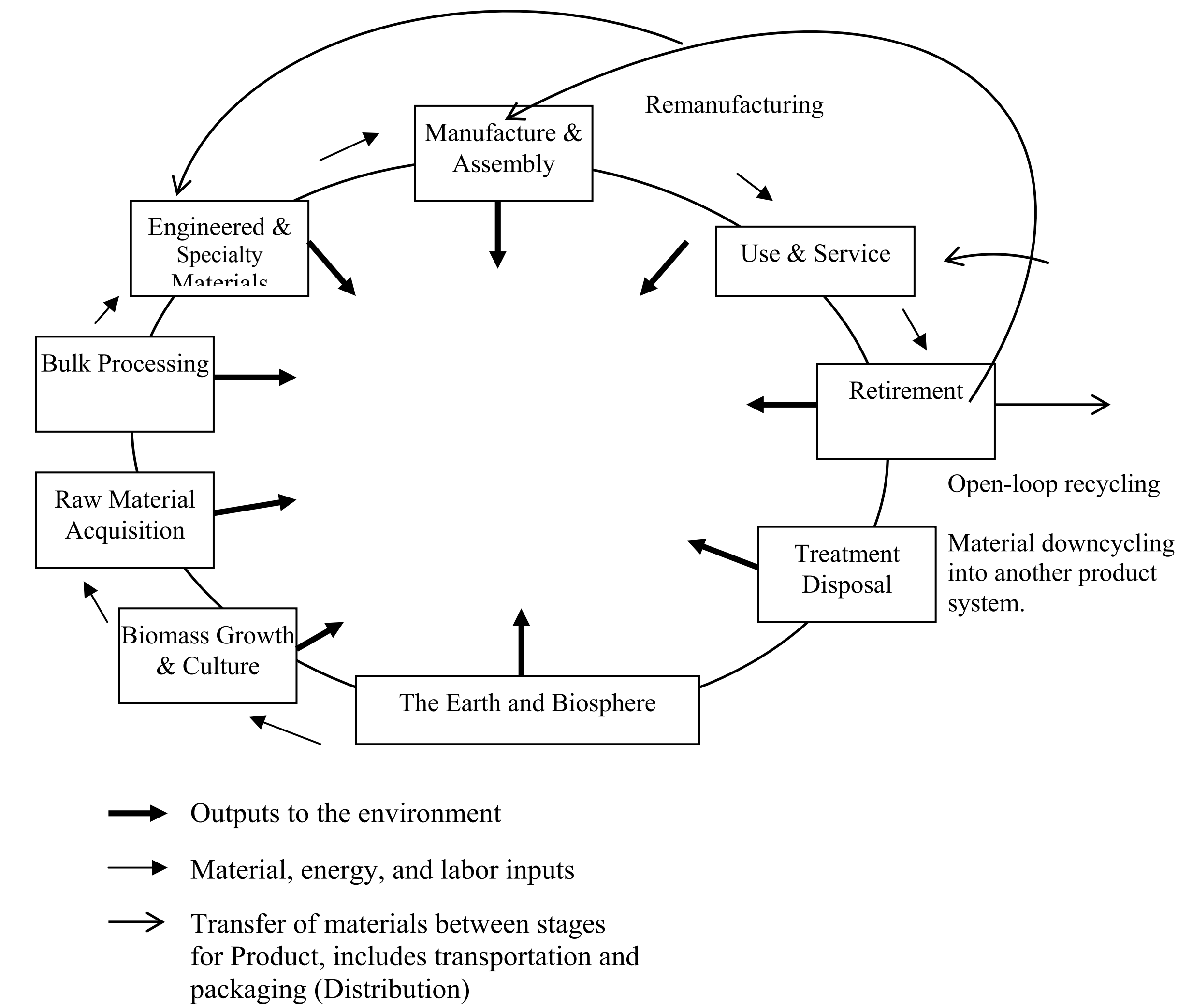

Figure 1.1 Integrated Life-cycle of Biological Materials
Source: (CORRIM 1998). Adapted from Keoleian and Menerey 1993.

CORRIM II is a non-profit corporation of scientists governed by a Board of Directors composed of representatives from the member research institutions (Table 1.1). Advisory roles include government agencies and other international cooperators.

Table 1.1 The Research Organizations Comprising CORRIM II

• University of Idaho	• University of Minnesota
• University of Maine	• Syracuse University New York
• Purdue University	• University of Tennessee
• University of Washington	• Mississippi State University
• Oregon State University	• North Carolina State University
• Virginia Tech University	• Louisiana State University (Currently inactive)
• Washington State University (Currently inactive)	• Forest Innovations, previously Forintek Canada Corp.
• APA—The Engineered Wood Association	• Composite Panel Association
• Western Wood Products Association	• USDA-Forest Service Research and Forest Products Laboratory (Advisory)
• Athena Sustainable Materials Institute (Non member cooperator)	

Brief Historical Perspective: In 1994, CORRIM II responded to a request for proposals made by the American Forest and Paper Association (AF&PA) as part of its Agenda 2020 program. The Agenda 2020 program focuses on pre-competitive research needs of the US forest products industry. The 1994 request targeted two principal research objectives relative to environmental life cycle assessment: (1) an updated analysis of the environmental efficacy of renewable building materials, including consideration of environmental impacts related to energy consumption, and (2) the identification of alternatives for reducing environmental releases associated with building materials through their life-cycles. In 1996, the US Department of Energy and the forest products industry funded CORRIM II to develop a research plan. The research plan released in January 1998 outlined activity for 22 modules over a 5-year span (Table 1.2), (CORRIM 1998). Protocols and standards were described in a set of Research Guidelines for the research plan to ensure that data collection, analysis, reporting and review would be compatible with ISO life-cycle assessment guidelines (ISO 2006) and life cycle inventory (LCI) procedures developed for the forest industry (AF&PA 1996) and have been revised periodically with changes in ISO guidelines.

Table 1.2 CORRIM II Research Modules – (from CORRIM 1998) Phase I and II Highlighted Areas

FOCUS AREA	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Forest Resource	**1. Forest Resource I Regional – NW/SE $400**		13. Forest Resources II Regional – NE-NC/IW/Canada $400			
Manufacturing Processes	**2. Processes I Structural Products $400**		14. Processes II Nonstructural Products $600			
Structures	**3. Structures Ia Component Systems $200**		5. Structures Ib Complete Structures $200		16. Structures II Alternatives $200	
Data Management	**4. Data Management (Funded as part of each module)**					
Industrial Products		6. Industrial Products Treated/Untreated $150				20 Structures III Infrastructures $150
Integrated Modeling		**7. Integrated Modeling $200**		17 & 21. Integrated Modeling II a&b $300		
Nonstructural Products		8. Nonstructural Products I Windows/doors/insulation etc.			18. Nonstructural Products II Millwork, flooring, etc. $200	
Products Substitution		9. Substitution I Components $200		15. Substitution IIa Comprehensive Structure $200		19. Substitution IIb Nonstructural $100
Biomass	10. Biomass Process for Energy $200					
Use, Disposal, Life Expectancy, Durability		11. Life Expectance/Durability $150		**12. Use/Maintenance/Disposal/ Final Recycle $300**		
Reporting		22. Reporting/Technology Transfer $250				
Total Funding Need	**$5000**					

All estimated funding (monetary figures) are in $ 000's
The initial budget proposal (highlighted in Table 1.2) was modified in scope (simplifications) and time (delays) to match available funding.

Preceding the CORRIM II initiative was a project to develop current environmental performance information for building materials used in Canada. This project, titled "Building Materials in the Context of Sustainable Development", was initiated in 1990 as the ATHENA™ project by FORINTEK Canada Corp, and is now continuing at the ATHENA™ Sustainable Materials Institute. In 1997, an alliance was established between CORRIM and ATHENA™ to take advantage of previous ATHENA™ research and to broaden the geographic and product representation of research.

1.2 Objectives, Modular Design, and Scope of CORRIM Phase I & II

Funding[2] to conduct a first phase effort (modules 1-4, 7, and a portion of 12 as highlighted portions of Table 1.1), was made available to pilot test the procedures that would be needed for the ultimate development of the full 22-module CORRIM II research plan. The Phase I effort fulfilled two critical objectives:

- to develop an adequate database and models of environmental performance measures over the entire life-cycles of structural building materials, beginning with extraction of resources, through product manufacture and transportation, construction of a structure, use and maintenance of the structure, and finally dismantling of the structure and either disposal or recycling of the building components; and
- to examine a range of management, product, and process alternatives to identify strategies that can improve the environmental performance of sustainable building materials.

The Phase I research effort concentrated on the development of LCI data for wood-based building materials produced in the two regions of the US that account for the greatest production of forest products – the Pacific Northwest (PNW) and the Southeast (SE). Further, because of funding limitations, the scope of Phase I was limited to consideration of the structural shells or envelopes of residential buildings excluding internal and non-structural materials such as trim, cabinets, lighting, heating, and appliances. Although focused on wood-based materials, Phase I research did address environmental performance of wood-framed buildings in comparison to residential buildings framed with steel and concrete block.

To a very large degree, wood, steel and concrete are used in every building with each being used where they hold some economic and or structural performance advantage. Each can be used as the primary framing method and for residential buildings wood frame structures are dominant with 86% of the market followed by concrete with 9% and steel with 2% including both single- and multi-family wall systems (APA 2002). The concrete share is higher in the Southeast and Southwest although still substantially behind the share for wood frame. Even when the primary material used for framing is changed, it represents a rather small change to the overall bill of materials in the house, as low as 6% on a weight basis, so the share of wood frame houses is not a very useful indicator of material usage. In that sense the framing materials appear to be more complimentary than competitive. There are however substantial opportunities for materials to compete in other housing applications. Also, light commercial buildings represent a substantial market for wood materials to be used. LCI Data for the non-wood materials was obtained from the Athena Sustainable Materials Institute which with periodic updating from many sources has become the same as the data provided in USLCI primary product database for all materials managed by NREL.

The Phase II Research Plan extended coverage to portions of modules 5,9,13,14, and 18 of the original research plan (highlighted portions of Table 1.1). Phase II had the benefits of the multiple stages of review from the Phase I Plan and focused on extending the geographic product coverage to all the major US Supply Regions by adding Northeast-Northcentral (NE-NC) and Inland Northwest (INW) forest resources and products. It also extended the products coverage to the largest non-structural wood products (particleboard, medium density fiberboard (MDF), and US produced resins). To extend the geographic coverage for the Life Cycle Assessments of buildings, West coast housing (single and multi-family) and non-residential light commercial structures designed to local seismic codes were added.

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[2] Phase I funding sources included contributions from USFS FPL, Weyerhaeuser, Simpson, Longview Fiber, Georgia Pacific, Louisiana Pacific, Temple Inland, Potlatch, International Paper, Champion, in cooperation with matching funds from University of Washington, University of Minnesota, Oregon State University, Virginia Tech University, North Carolina State University, Mississippi State University, and University of Idaho. Phase II funding included additional support from University of Maine, Syracuse University New York, and associations involved in research and testing of materials including the American Plywood Association, Western Wood Products Association, and Composite Panels Association.

1.3 Research Team

To complete the Phase II analysis more research institutions became participants providing regional and product specific expertise (21 authors from 10 research institutions) as noted in Table 1.2.

Table 1.3 Lead Scientists Involved in CORRIM - Phase II Chair of Stages of Processing, Jim Wilson, Professor Emeritus, Oregon State University

Contribution	Principal Investigator	Member Institution
Stages of Processing Modules Oversight	Jim Wilson	Oregon State University
Forest Resources Modules		
Forest Resources Integration	Leonard Johnson Bruce Lippke	University of Idaho University of Washington
Forest Management Inland Northwest	Elaine Oneil Jim McCarter	University of Washington University of Washington
Forest Management NE-NC	Marc McDill Jim Finley Paul Roth	Penn State Penn State Penn State
Forest Engineering NE-NC	Joe McNeil Xiensung Wang	West Virginia University West Virginia University
Growth/Disturbance Carbon Modeling	Elaine Oneil Bruce Lippke Jim McCarter	University of Washington University of Washington University of Washington
Process Modules		
Softwood lumber-Inland (INW)	Francis Wagner Maureen Puettmann	University of Idaho WoodLife (Consulting)
Hardwood & Softwood lumber- NE-NC	Scott Bowe Richard Bergman	University of Wisconsin University of Wisconsin
Particleboard, MDF andResins	Jim Wilson	Oregon State University
Hardwood Flooring (NE-NC)	Scott Bowe Steve Hubbard	University of Wisconsin University of Wisconsin
Cradle to Construction Gate LCIs	Maureen Puettmann Jim Wilson	WoodLife (Consulting) Oregon State University
Structures Modules		
Subassembly Component Impacts	Bruce Lippke Lucy Edmonds	University of Washington University of Washington
West Coast Structures & Seismic Standards	Jamie Meil Mark Lucuik	Athena Institute Marsh Hershfield

1.4 Report Structure

This report on the Phase II research extends the coverage of the Phase I Report (Boyer et al 2005) to all major US supply regions (Phase I: PNW & SE forest resources, structural products, Phase II NE-NC & INW structural products and hardwood flooring), includes large volume non-structural product LCIs (particleboard, MDF, and US resins), and provides more detail on structural analysis both in terms of west coast regions, seismic standards, and subassembly component level impacts.

This report provides a brief summary of the introduction of research guidelines and methods that were developed in the Phase I report to reduce the need for cross referencing. The report organization is otherwise similar to the Phase I Report, including summary integrative material in the body of the report followed by individual research modules for developing the product LCIs and system LCAs. These modules are in effect stand-alone reports covering each stage of processing. The modules are:

- **Module A: Forest Resources – INW region, NE-NC Region–** identifies environmental performance measures and presents life cycle inventory data for specific unit operations in woodland management activities in forests of the Inland Northwest as well as the Northeast-Northcentral covering a range of species management practices and ownership groups for each region.

  The objectives of this module are to:

  - Provide environmental, energy, and resource impact data on the growth, management, harvesting and reforestation of timber for a range of management intensity scenarios.
  - Develop case studies to represent a typical range of forest management objectives and stand and site conditions.
  - Provide economic data for the case studies that can be used in environmental improvement analysis.
  - Provide environmental performance measures including carbon and primary change agents such as fire suppression that affects forest density and the risk of substantial forest altering disturbance i.e. wildfire, disease and insect epidemics.
  - Provide inputs for the Processing Modules from the case study scenarios.

- **Module B: Softwood Lumber** – **INW Region**– presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Inland Northwest region of the United States.

  The objectives of this module, as well as modules C-D (other products and regions) are to:

  - Provide environmental, energy, and resource impact data on the manufacture of a specific product in a specific supply region.
  - Provide benchmarks for these products that will enable comparison to process improvements or new processes.
  - Provide economic bench mark data that can be used in environmental improvement analysis.
  - Provide input for the Structures Module.
  - Provide an accounting of carbon and compare fossil versus biomass fuel dependency.
  - Provide a measure of resource use efficiency.

- **Module C: Softwood Lumber Production – NE-NC Region** – presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Northeast-Northcentral region of the United States.

- **Module D: Hardwood Lumber Production** – **NE-NC Region** – presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Northeast-Northcentral region of the United States.

- **Module E: Hardwood Flooring Production** – NE-NC Region presents life cycle inventory data for hardwood flooring, a separately funded project linked to Module D.
- **Module F: Particleboard Production** – United States (US) presents life cycle inventory data for specific unit operations associated with the manufacture of Particleboard across the US.
- **Module G: Medium-density-fiberboard (MDF) – PNW and SE** – presents life cycle inventory data for specific unit operations associated with the manufacture of MDF across the United States.
- **Module H: US Resins** – presents life cycle inventory data for specific unit operations associated with the manufacture of US resins across the United States. This data is intended to replace the resin data used in Phase I in order to upgrade the data quality for products based on US resins instead of international resin sources that were used as the default for Phase I research.
- **Module I: Life Cycle Assessment of Structural Floor and Wall Assemblies and their relative component impacts –** provides information on the relative contributions of different components in wall and floor designs.
- **Module J: Design and Life Cycle Assessment of Residential Building Shells for West Coast Locations subject to Seismic Standards –** outlines the design of typical light-frame residential structures for west coast locations based on Seattle for a cooler, wetter climate, and Los Angeles for a warmer dryer climate. (The report currently available focuses exclusively on the impact of seismic codes, not alternative building designs).

  The objectives of this module are to:

  - Provide environmental, energy, and resource impacts resulting from code changes to meet seismic requirements.
- **Module K: Life Cycle Carbon Impacts of Forest Management subject to fire and insect disturbance risk–** provides information on carbon sequestration in forests, products and fossil fuel substitution for forest under high disturbance risk such as the dry Inland Northwest.

  The objectives of this module are to trace the impacts of forest management, processing of products, biomass conversion to energy and the substitution of non-wood materials on carbon mitigation to:

  - Provide information on the integrated impacts of forest management and construction on carbon pools.
  - Demonstrate the impact of different management alternatives (both passive with regard to disturbance risk, and active risk reduction including forest health restoration) on carbon through the life cycle of the forest through the product flows serving construction.
  - Provide case study information for large-scale landscapes as well as the forest stand level.
- **Module L: Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Southeastern United States** – presents life cycle inventory data for specific unit operations associated with the manufacture of softwood lumber in the Southeastern region of the United States.
- **Module M: Impact of Increasing Biofuel Use in Solid Wood Production** (this module was transferred to a Phase III Research Plan to develop LCI data for collection of forest residuals and other woody biofuel feedstock as well as LCI data for three primary processing alternatives (pyrolysis, gasification, and fermentation)

  The objectives of this module are to:

  - Evaluate the impact of increased use of biofuels in production such as may be purchased from other mills, collected from thinnings or forest residuals or diverted from other low valued uses such as landscaping.
  - Establish the LCI improvement potential for biofuel self sufficiency.

1.5 Report Reviews and Conformity with ISO 14040 series

The entire Phase I report was reviewed internally for consistency by many of the 23 authors of the report. Many sections of the report were made available to outside experts and their comments were incorporated. Critical external reviews were conducted of the LCI and LCA process for compliance with the assessments within the ISO 14'040s standards with results published in the Phase I Report. Given the depth of Phase I reviews and inconsequential changes in methods, in addition to the internal reviews and outsider with expertise in the data, the Phase II Report was reduced to a series of journal articles with each article subjected to double blind reviews with acceptance for publication dependent upon the review process.

The primary LCI/LCA issues from prior reviews remain:

1) Allocation of burdens based on mass, our most consistent metric, remains the standard for LCI/LCA work and was specified in our Research Guideline. The Phase I review recommendation to consider a value allocation method is controversial. Our limited sensitivity analysis would not suggest it will significantly alter results and for such a large database project it is beyond our scope to provide a consistent methodology other than a mass allocation method. Furthermore, the mass allocation method was consistent for the secondary product data we access in the ATHENA EIE model (Athena Institute 2004). Constructing a value scheme has intuitive appeal but involves arbitrary allocations that are not stable over time and as such becomes more problematic than a well-quantified mass system. Our analysis of carbon under the assumption that all low-grade co-products are used as hog fuel provides an important sensitivity analysis as it represents a substantial reduction in the burdens assigned to co-products but did not reveal a magnitude of change that would alter conclusions. In fact by diverting co-products to energy production, most wood products become energy self sufficient, substantially reducing emissions caused by the consumption of fossil fuels. Future research to evaluate the sensitivity of different allocation methods would be appropriate but is not a current high priority for CORRIM research. It will be considered if new products appear to be particularly sensitive to allocation methods. Co-product allocation sensitive to changing carbon prices resulting from carbon mitigation policy would eliminate the ability to provide comparisons across projects and would be better considered as a carbon price sensitivity analysis.

2) An assessment of data accuracy involving so many measurements is difficult. The range of variation in the primary survey data describes a range corresponding to an array of practices from something like best to worst except that our sample was not stratified to cover the full range of facilities. We can generally expect over time that the trend will favor investing in best practices. While we did obtain a large response to our survey, representing anywhere from 10 to 50% of total industry production for a given product and region, they were not randomly selected. However we took many steps to ensure that the data were accurate including having a project leader very familiar with their primary industry, conducting mass and energy balances of data, comparing data from plants within a region and between regions, and did follow up contacts to resolve outlier data. The range of data is not generally reported because it was not collected to be representative of all practices in the industry but is available in our SimaPro models. Our primary data collection at the unit process level does provide accuracy substantial better than using industry averages as well as substantially better than impacts beyond the end of product life such as the fate of carbon in landfills.

3) It is very time consuming and costly to perform a comprehensive sensitivity analysis on the integrated results involving so many products and processes. We did do sensitivity analysis we thought critical such as diverting more co-products to internally consumed hog fuel, forest management alternatives, drying etc. Future research to evaluate the sensitivities of integrated results to the range of variation in survey data would be appropriate but is not likely to alter conclusions and is therefore not a current high priority for CORRIM research.

4) It was recommended that we include the resource LCI in the product LCI, along with the transportation. Our analysis was designed to provide gate-to-gate analysis in modules. We roll up all the LCI data into a forest-to-building LCA cradle to gate report. The rationale for this modularization was to provide the module results for inclusion in ATHENA EIE and the US LCI Database (NREL 2008). In our Phase II effort we have given a high priority to developing cradle-to-gate product LCIs along with a table of add-on LCIs for transportation from the product manufacturing gate to the building site. Product LCIs for the structural wood products that include the resource are currently being added to the US LCI Database.

5) It was recommended that we include the energy content for wood materials. Again to be consistent with CORRIM protocol, ATHENA EIE, and the US LCI Database project we do not consider the feedstock energy of wood like we do for natural gas, crude oil, coal, and uranium. In the US wood is not normally considered a fuel, and especially not when it is generated during demolition or recycling. Whereas, natural gas, crude oil, coal, and uranium are considered fuels, so their energy content is included. We clearly point out that the energy content of wood products is not considered except when used as hogfuel, an internal use.

The journal articles published from the Phase II research conformed to the double blind process and as such comments are not available. Module J on the impact of seismic standards was not published as a journal article since the reviewers wanted a substantial update of the building codes, which was not possible within existing budgets and would ultimately be undertaken at a later point in time with the final release of the ATHENA EIE model that would be used for the assessment. Module J does provide the best interim assessment of the impact of seismic codes on LCI/LCA data and is included here pending future updates of the material and formal reviews.

2.0 Life Cycle Analysis Framework

2.1 Introduction

(For convenience to the reader not familiar with life cycle methods we have retained much of the description of the Analysis Framework published in the Phase I Report in Section 2.0. Section 3.0 begins the summary of the Phase II research findings.)

Life-cycle assessment (LCA), which began in the 1960s, has evolved as an internationally accepted way to address complex impact questions regarding the assessment of processes with complex inputs and outputs and their effects on the environment. “Life-cycle” refers to all activities from forest resource regeneration or mineral extraction through product manufacturing, to the end use of these products and their eventual disposal or recycle, i.e. from “cradle to grave” (Curran 1996). Guidelines to conduct LCAs are set forth in the ISO 14000 series of standards with periodic updates (ISO 2006). Counterpart national standards have been adopted in many countries and have been translated into guidelines for specific industries, an example of which is the AF&PA user’s guide for the US forest industry (AF&PA 1996).

2.2 CORRIM Framework and Guidelines

Figure 1.1 illustrates the overall approach employed by CORRIM to study biologically-based materials, and identifies the linkages between the major steps in the life-cycle of a building structure. Protocols and standards are described in the CORRIM research guidelines (CORRIM 2001) to ensure that data and analysis are consistent with methods for performing life-cycle inventories and life cycle analyses as set forth in the ISO 14000 series of standards and AF&PA guidelines for the forest industry.

2.3 Life Cycle Assessment (LCA)

Figure 2.1 presents the general flows in a typical "cradle-to-grave" LCA and Figure 2.2 illustrates the major components of an LCA study. An LCA begins with an initiation phase during which a problem is defined along with the scope, system boundaries, data categories, and review process. Initiation is followed by three interrelated phases that may be conducted simultaneously or in a sequence that best suits the problem being studied: a life cycle inventory phase that identifies and quantifies the energy, resource use and environmental effects of a particular product, service, or activity; an impact assessment phase which investigates the potential environmental consequences of energy and natural resource consumption and waste releases associated with the system being studied; and an improvement assessment phase where opportunities to reduce environmental impacts and resource use are investigated. Figure 2.2 highlights some of the factors likely to be considered within each phase and emphasizes the iterative nature of the process.

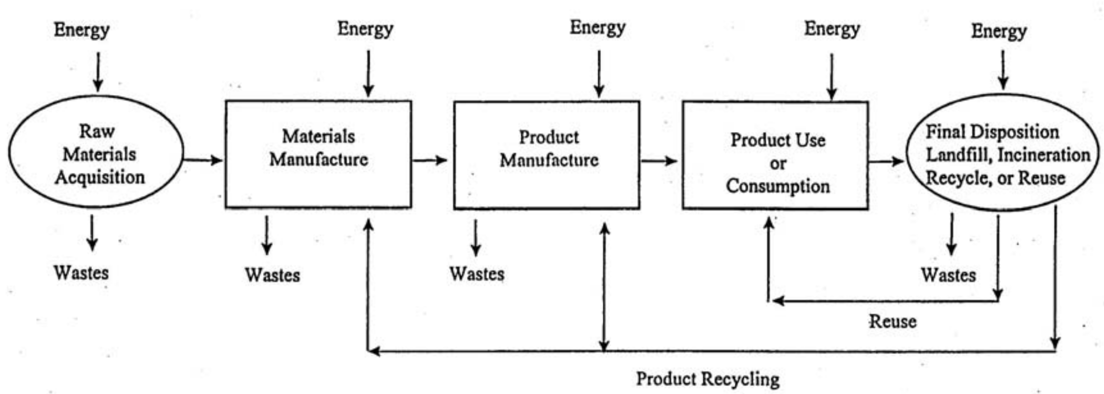

Figure 2.1 General Flows in a "Cradle-to-Grave" LCA System
Source: Franklin Associates 1990

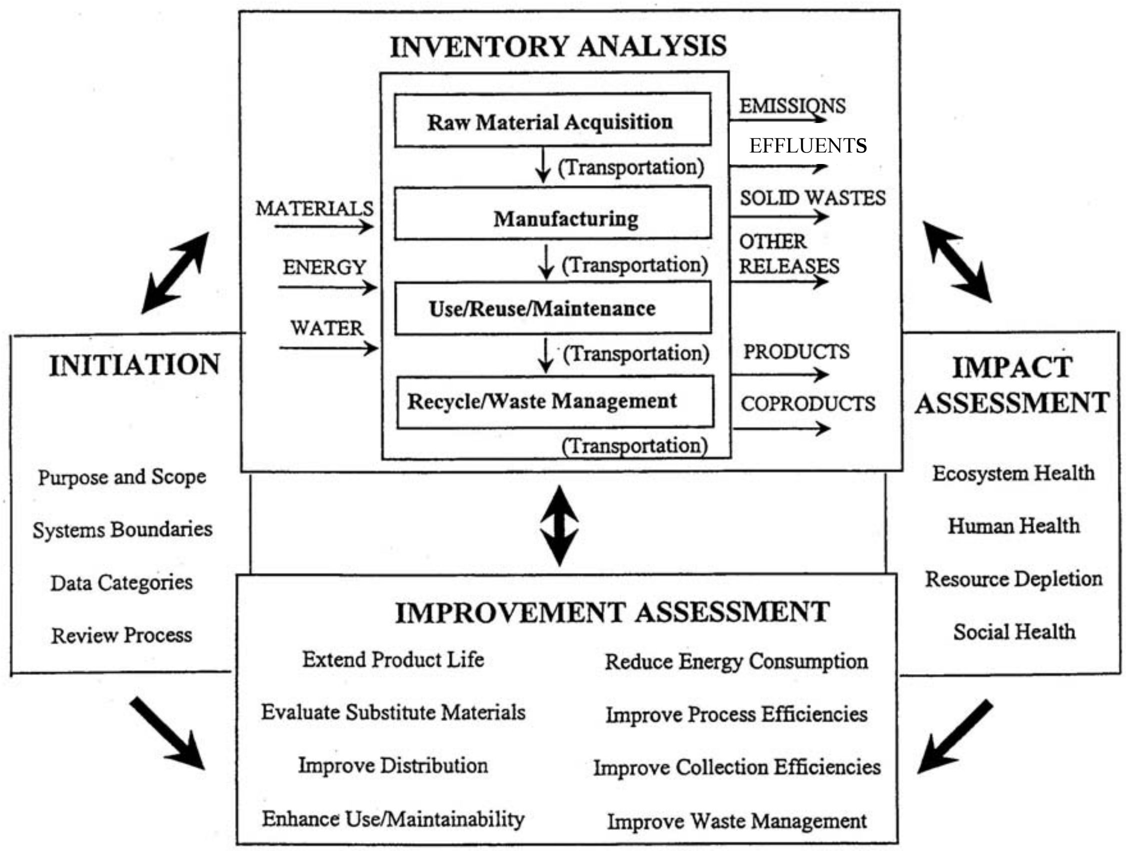

Figure 2.2 Main Components of an LCA Study
Source: ATHENA 1997a

2.4 Casting the CORRIM Framework in the LCA Context: Life-Cycle Stages

The similarity between the CORRIM framework in Figure 1.1 and the generic life-cycle approach presented in Figure 2.1 is evident. There are, however, two rather unique features of the CORRIM framework.

First, while some LCAs involving agricultural products or bio-energy have expanded the generic model by including a crop growing stage prior to raw material acquisition (Andersson & Ohlsson 1999, Mann & Spath 1997), forest growth is more complex. The relative complexity of forest growth is due to 1) the much longer time frame involved, 2) the use of intermediate harvests (thinning) to yield products, 3) the broader array of joint products arising from a single tree (saw, veneer, and pulp logs) and stand (due to mixed species having different use preferences), and 4) the unique set of forest co-products (water, recreation, berries and mushrooms, etc.) and environmental effects (such as water quality, species diversity, wildlife habitat, and carbon sequestration).

Second, buildings, which account for the largest use of wood in North America and the main focus of this study, are unique in their size, complexity, and longevity. For example, a residential home is constructed, used for a long period of time, and eventually demolished. The period of use and occupancy involves cycles of maintenance and repair (e.g. re-roofing) and may involve a series of owners each of which may remodel the structure to accommodate changes in desired functionality and aesthetics. As a result, the time frame between when tree seed germinates and when a home is demolished could be on the order of one to several centuries or more. Thus, the temporal distribution of events and associated environmental effects during the seed to demolition life-cycle must be considered; merely summing all of the events and effects would produce the naïve and meaningless result that all of the activities and associated impacts occur simultaneously.

Table 2.1 highlights the major differences between the generic LCA model and the CORRIM framework. The major stages in the generic LCA model evolved for investigating consumer products and packaging materials with short lives where a simple temporal summation of effects is reasonable. Table 2.1 also indicates a rough estimate of time associated with each of the components of the CORRIM framework with comments identifying some of the associated activities and environmental effects. The procedure developed by CORRIM to deal with these temporal issues in LCA is discussed more fully in Section 2.6. Identification of these temporal aspects of the forestry and housing components leads to Figure 2.3, which shows the major stages in the cradle-to-grave cycle of a building such as a residential home and also illustrates the two long-term stages (forest growing and use of the building) that are important for carbon storage.

Table 2.1 Comparison of the Generic LCA Model and the CORRIM Research Framework

Generic LCA Model	CORRIM	Comment
	Forest Growth Time frame: 25-100^{+} years	Nursery, planting, thinning, fertilizing, during the growth cycle. Effects on carbon sequestration/global warming, diversity, habitat, streamside conditions, etc.
Raw Material Acquisition	Harvesting Time frame: < 1 year	Logging during commercial thinning or final harvest. Effects on soil compaction and productivity, diversity, habitat, siltation, etc.
Manufacturing	Manufacturing Processes Time frame: < 1 year	Individual products (lumber, plywood, LVL, OSB, etc) Assemblies of products (trusses, glulam beams, I-joists, etc.). Effects on air & water emissions, solid waste.
	Construction of Structures Time frame: < 1 year	On-site or factory built components (floor, wall, roof) and finished structure. Effects on solid waste.
Use/Reuse/Maintenance	Service Life & Use Time frame: 40-100 + years House life:75 + years	Maintenance cycles (painting, re-roofing, siding, etc.) and remodeling. Effects on energy use & associated emissions/waste, energy & emissions associated with repair/remodel products.
Recycle/Waste Management	Recycling & Disposal Time frame: < 1 year	Teardown, segregation of materials, recycle, combust for energy, landfill. Effects on energy use & substitution, air & water emissions, solid waste/carbon sequestration.

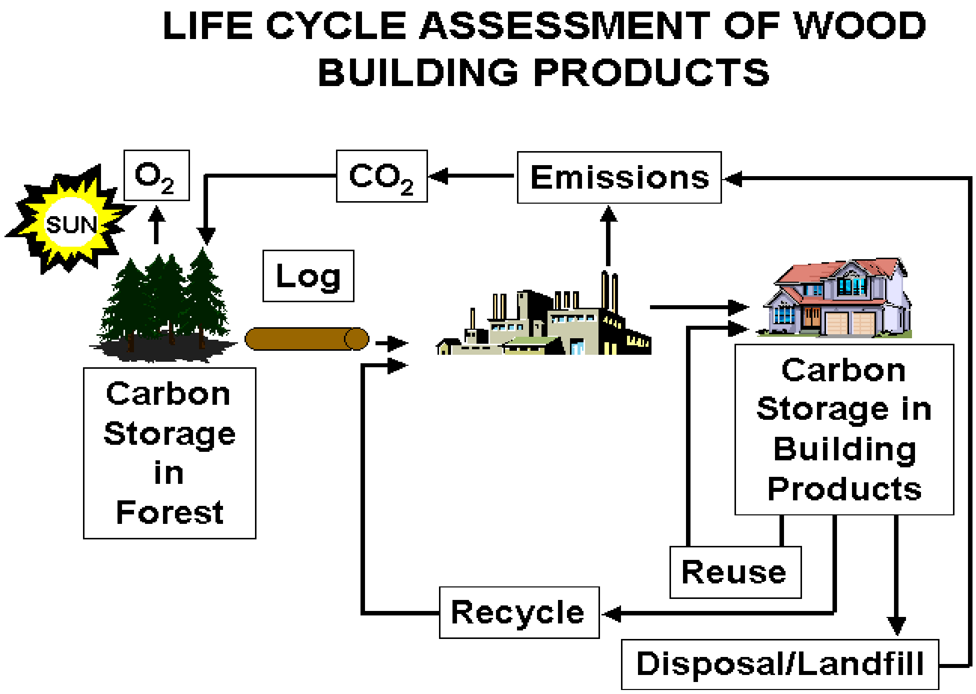

Figure 2.3 A Depiction of CORRIM's Research

2.4.1 LCA Components

Table 2.1 and Figure 2.3 suggest that the LCA of a building system is a composite of many separate, but interrelated, LCAs. A building system LCA is created through cumulatively embedding the LCAs of many processes and their associated products, sub-assemblies and assemblies, each containing a specific set of life cycle stages from raw materials through recycling and waste management. For some products, certain stages may become deferred and be dependent on the aggregated LCA of the entire building of which they become a part. Examples are wall studs and other main framing lumber products that are covered by other materials and remain unchanged during the building life; these items typically have no maintenance stage of their own. Similarly, the recycling and disposal stage may apply to only some of the products when the building is finally demolished (i.e. recycling and disposal of these individual products is not separable from the building as a whole).

2.4.2 Initiation and Scope of Phase I&II

Construction of a complete residential home can be viewed as involving three categories of component LCAs. The first of these includes all of the products and assemblies required to produce the structural skeleton of the building. The second category involves additional products, such as siding, insulation, and roof topping, to complete the building envelope. The third category involves products and activities to complete the interior.

As noted earlier, the scope of Phase I CORRIM research is restricted to a study of a subset of the overall system. This subset includes:

1. Forest growth and harvesting and product manufacturing in the US Pacific Northwest, SE, NE-NC including hardwoods, and Inland Northwest. These four regions are the predominant suppliers of domestically manufactured wood building materials.

2. Wood products and assemblies needed to create the closed-in building envelopes that meet the requirements of prevailing building codes in a warm climate (Atlanta, GA) and a cold climate (Minneapolis, MN) were included in Phase I and extended to include Seismic requirements for Seattle and Los Angles as north and south extremes for the West Coast.

Methods developed for these selected regions and codes can be adapted to other regions or sub-regions. The overall research plan also anticipates extending the analysis to interior finishing and nonstructural exterior work.

2.4.3 Inventory Analysis and Data Collection

Many types of data can be acquired to estimate production and environmental performance measures for each process, all of which have been used to some degree by other life-cycle researchers. However, it is important to distinguish between primary and secondary data. Primary data are those collected using recognized inventory data collection rules from specific facilities or operations; such data is typically labeled to indicate the date of collection and the estimated reliability of the data. Secondary data are those obtained from secondary sources such as simulation studies, or published articles containing industry or region-wide, or company specific information. The various areas of study within CORRIM are discussed in the following paragraphs, with commentary regarding the type of data collected.

Forest Growth and Harvesting

Production of output from a forest ecosystem involves activities associated with establishment and growth of trees and other vegetation, the removal of wood biomass used as input into product manufacturing processes, and associated impacts on non-wood forest co-products including water, habitat, diversity, and aesthetics. These impacts change through time due to basic tree and plant physiology and competitive stand dynamics, past and prospective technologies, evolving silvicultural practices, and population demands for forest outputs. Time is a critical element since the period from establishment to removal can vary from a few years for short rotation, intensive culture fiber/energy plantations to a century or more for selectively managed forests. Life-cycle inputs and outputs include both quantitative measures of productivity, costs, and environmental effects and qualitative measures that describe difficult to measure aspects of the forest environment.

Consideration of the environmental impacts to a forest requires a landscape approach since management levels of varying intensity, including no management, are applied differentially to sites of different productive capability and age classes that are often adjacent to one another. The blend of management intensities and age classes within a landscape is important in developing a balanced perspective on quantitative and qualitative outputs and effects. The approach taken by CORRIM with respect to forest growth and harvesting is to construct scenarios describing conditions associated with the growth, removal and establishment of forests for each region (Pacific Northwest, and Southeast) and to use forest simulation models that have been calibrated to forest inventory plot measurements to estimate the effect of site productivity and management intensity on the following two categories of measures.

- Quantities of products (sawlog, veneer log, pulp log), costs, resources consumed (energy, fertilizer, etc.), and associated emissions factors that are passed to the product manufacturing stage (Module A).
- Measures of effects on diversity and habitat, stream quality, etc. that are unique to the forest resource stage and provide indications of the impact of the forest activity (Module O).

All of the input and output data compiled by CORRIM Phase I research on forest growing and harvesting activities are based on regional forest growth and yield models and recent studies of harvesting systems reported in the literature. The stratification of harvesting systems and growth models specific to regional forest types produces representative average measures for each region. No direct field studies were commissioned by CORRIM however many field inquiries were made to verify the data and methods used.

Product Manufacturing & Unit Processes

An objective of Phase I and Phase II was to treat each major step of each manufacturing process as a separate unit ("unit process") for data collection. For example, a sawmill can be viewed as consisting of the following processing centers (or unit processes): log yard, debarking and bucking, primary breakdown of logs into trimmed, green lumber; kiln drying, planer mill, and grading and packaging. This level of detail allows for recognition of various product grades and joint products from each center that may be sold to other industries without further processing. It also recognizes alternative pathways of primary material through the mill (green lumber to grading & packaging versus green lumber to kiln drying). By performing data collection at the unit process level, many potential issues with respect to co-product allocation can be resolved and differences among various technological configurations for a unit process can be examined. Data for individual unit processes and facilities will vary by plant age and type, and factors such as transportation distances will also vary by region. Sampling individual facilities and unit processes provides a sense of the variation in the industry and permits summarization that provides the range, median, mode and upper/lower quartiles. This permits analyses that can focus on the sensitivity of outcomes to advances in adoption of technology such as indicated by the rhetorical question: "What happens as the industry gradually improves so the average moves up to the current upper quartile?"

CORRIM Phase I & II involved gathering of current data through questionnaires sent to selected individual manufacturers. Table 2.2 lists wood products and assemblies for which CORRIM data has been collected from manufacturers during Phase I&II

Table 2.2 Wood Products for Which Unit Process Data has been Collected by CORRIM

US Softwood lumber, kiln dried (SE, PNW, NE-NC, INW
US Softwood lumber, green (PNW)
US Hardwood lumber, (NE-NC)
US Hardwood flooring (NE-NC)
US Softwood plywood (SE, PNW)
US Oriented strandboard, OSB, (SE)
US Glue laminated beams (SE, PNW)
US Laminated veneer lumber, LVL, (SE, PNW)
US Wood "I" joists & beams (SE, PNW)
US Particleboard (US)
US Medium density fiberboard, MDF (US)
US Resins for use with laminated products (US)

Construction of buildings also involves consumption of non-wood materials such as concrete for foundations and steel for nails and fasteners, etc. Life-cycle data for these materials and products were taken from previous life-cycle studies compiled or conducted by the Athena Sustainable Materials Institute. Table 2.3 lists products for which CORRIM is using data from previously published LCAs during Phase I.

Table 2.3. Products Considered in CORRIM Using Data from Studies Conducted by the Athena Sustainable Materials Institute

Material	Product Considered
Concrete	• 10, 15, and 20 MPA ready mix • Precast double T beams • Precast hollow deck • Standard concrete blocks • Cement mortar
Steel	• Painted trusses (bar joists) • Galvanized studs • Galvanized decking • Composite steel/wood joist components • Reinforcement bar • Painted hollow structural steel • Painted tubing • Painted heavy sections • Painted light sections • Hot & cold rolled sheet • Welded wire mesh & ladder wire • Nails and Fasteners

Building Construction

Construction of a building involves a fundamental shift from individual products to the combination of these into building assemblies (wall, floor, and roof systems) using spans, loads, and other variables that comply with building codes. The activities associated with construction include those involved in producing building materials, as well as new life-cycle steps and impacts tied to construction activity in which materials and energy are consumed, and solid wastes and emissions are produced. Some effects are simply the aggregate of the various materials used in the construction assemblies while others are unique to the construction activities and are not attributable to an individual component product. To integrate various combinations of products into functionally equivalent assemblies and completed structures, CORRIM used the Environmental Impact Estimator (EIE model) of ATHENA™ which contains more than 50 different assemblies incorporating combinations of concrete, steel, and wood products. Working with ATHENA™ researchers, CORRIM developed additional structural designs based on residential building codes in Minneapolis, MN and Atlanta, GA to represent cold and warm climate conditions, respectively (Phase I Modules I and J).

Building Use and Maintenance

The structural materials and assemblies generally require little direct maintenance during the operational life of a building unlike siding, roofing and other assemblies required to fully complete the exterior of a building. Since the dominant exterior maintenance requirement is roofing which is common to all building designs examined, the environmental performance estimates for maintenance (Phase I Module L) do not identify different impacts for different framing methods and are relatively small compared to the impact of construction or building use.

Energy consumption during the operational life of the building and maintenance of the shell have been estimated based on the average home in each city hence providing a perspective on the relative importance of these stages on overall life-cycle energy consumption and emissions (Phase I Module K and L).

Building Demolition and Material Recycling or Disposal
Recycling and waste management focus on the individual materials for which recycling and waste management opportunities differ greatly. Energy and emissions are involved in demolition/deconstruction, separation and transport of the materials, and in recycling and waste management processes. Since a building may not be demolished for many years after construction, accurate depiction of this stage would require forecasting technologies and markets for recycling and waste management far into the future. Since these conditions are unknown, CORRIM assumes that current practices are applicable (Module M). Furthermore, research suggests that demolition, recycling, and disposal differences between alternative designs are small (FORINTEK & Wayne B. Trusty 1997). Therefore, comparisons between design alternatives will be reasonably accurate in the absence of good data for this stage. However, when absolute effects of individual designs are required, better data for this stage may be necessary, a topic for future research.

2.4.4 Life Cycle Impact Assessment

Life cyle impact assessment (LCIA) is presently at a rudimentary stage since the environmental and human health consequences of emissions are difficult to quantify in that they depend on temporal and geographical dispersion, level and rate of exposure, and other factors. Furthermore, comparing these consequences involve value judgments that are often contentious. Some aspects of the CORRIM inventory analysis may be simultaneously viewed as impact assessment. For example, quantities of concrete, steel, and wood consumed relate to resource depletion. At this point CORRIM research is not explicitly focused on impact assessment beyond inferences associated with energy, water and materials consumption and the use of widely accepted environmental equivalence measures for some categories of emissions (e.g. expressing various greenhouse gases in CO_2 equivalents or global warming potential).

2.5 Improvement Analysis and Scenarios

Improvement analysis refers to using LCA results to suggest opportunities for environmental improvement or to evaluate proposed changes to a product, process, or design. Since improvement analysis often involves different technical expertise (process design engineers, product designers), and broader considerations (economic and market factors) than information gained from a life-cycle study, it is often conducted independently of LCA or as an adjunct to an LCA. However, through sensitivity and scenario analyses and studying material substitutions, CORRIM research will provide comparisons and insights that will assist analysts, designers, managers, and policy makers in understanding relative benefits and costs associated with alternatives and understanding which stages and unit processes in the life-cycle provide the greatest leverage for improvement.

2.6 Temporal Issues in the LCA Context

Many life cycle inventories are performed for non-durable products for which the time from resource extraction until post-consumer disposal was so short that the temporal distribution of events and associated impacts can be ignored. In contrast, the life cycle for CORRIM research covers a very long time frame, beginning with planting a forest stand, cultivating it to maturity, harvesting and converting logs into products that are assembled into buildings, tracking the activities during occupancy and use of the building until its eventual demolition and disposal. For CORRIM, the time dimension becomes great and presents difficulties that are not well discussed in the LCA literature. Some activities, such as the growth of a forest stand and associated carbon removals from the atmosphere and the consumption of energy for heating and cooling of a building, occur in relatively small annual quantities; the aggregate total when trees are harvested or when a building is demolished would be misleading since the totals and associated emissions did not occur in these specific single event years. Other events such as fertilization of the forest or re-roofing a building only occur at intervals so a total, expressed as if these events occurred simultaneously does not make sense. To properly deal with the timing of events and emissions and avoid misleading aggregations, CORRIM developed a method for portraying the life-cycle as a series of cohorts (forest stand and building age classes) that move through time. Correct accounting at any time point is the sum of the activities and emissions of those cohorts that coexist at that time. To illustrate, consider a simplified CORRIM life-cycle consisting of the following phases:

1. Forest Planting and Growth

   Carbon removal from the atmosphere and sequestration occurs annually through the growth phase that may take 25 to 100 years or more until harvest. Cultural activities and wood marketed from thinning occur periodically. Consider the following forest age cohorts and associated cultural activities:

   - Nursery: planting seed, irrigating, fertilizing and packaging/shipping for planting
   - Stand initiation: site preparation, planting seedlings on the forest site, weed control
   - Early stand culture: weeding, pre-commercial thinning, fertilizing, pruning
   - Middle stand culture: commercial thinnings, fertilizing
   - Mature stand: final harvest

   Unlike many LCAs of wood products, the CORRIM perspective, that includes forest growing, considers harvested logs as an intermediate product rather than the starting raw material. Raw materials in the CORRIM perspective are air, water, and solar energy used in photosynthesis, land, and fertilizers and fuels associated with the silviculture and harvesting activities.

2. Harvesting, Product Manufacture, and Building Construction

   The series of conversion and building processes from “stump to completed structure” that commonly takes 2 years or less

3. Building Occupancy and Use

   Building occupancy and use consumes annual energy for lighting, heating, and cooling plus periodic maintenance events. The building may be used for 25 to 100 years or more. Consider the following building age cohorts:

   - **Young:** relatively little maintenance, replacement, or remodeling occurs during the early use of a new home.
   - **Middle-aged:** the first cycle of maintenance and replacement activities begins, hence there is demand for materials to accomplish them as well as disposal issues for the replaced materials.
   - **Old-aged:** maintenance and replacement cycles may intensify as the house becomes outdated and homeowners undertake various remodeling steps.

2.6.1 Time-line Perspective of Cohorts

Figure 2.4 portrays the "cradle-to-grave" perspective for the cohorts with the time-line shown underneath; “h” is the age when the forest is harvested and “T” is the time when the building is demolished. The problem with the time-line perspective is that it creates some logic issues and violates the tenet that LCI is based on empirical, not forecast data. At any time chosen as the present, data for all activities beyond that time point are forecast data that must rely on assumptions regarding changes in technology and design. If the present is assumed to be the time of planting seed, can we assume that today’s building codes, design practices, and materials will be relevant when the home is built from these trees at h+2 years in the future? If not, what will the relevant codes, designs, and materials be? If thinnings are conducted, is it logical to pool them with the final harvest as inputs into the "stump to structure” stage? In the real world, no mill stores thinnings from a stand for 15 or 20 years in order to process them with the logs from the final harvest of that stand.

------------ Forest Growth -----------						------- Building Use -------			
N	P	PTF'	PTF	M	S/S	Y	M	O	D
Nursery	Plant	Prune Thin Fert	Prune Thin Fert	Mature	Stump to Structure	Young	Middle	Old	Dispose
0 .... h ....h+2...T									

Figure 2.4 The Time-Line of the CORRIM Life-Cycle

To illustrate a different type of problem, consider the final disposal of the building. The disposal, materials recovered, and emissions to the environment of a new building that will not be built until far into the future, and which will not be torn down until much later, are likely to be very different than the problems associated with tearing down and disposing of materials from the today's obsolete buildings. A question to be raised is "are we really interested in the cumulative impacts associated with planting seeds in a nursery and, perhaps 200 years into the future, tearing down and disposing of a building made from them?

2.6.2 Simultaneous Cohort Perspective

The difficulties with the time-line approach in Figure 2.4 can be overcome by recognizing that all cohorts exist simultaneously in a single time period (Figure 2.5). Today, nurseries are producing seedlings for planting on lands that were just harvested, there exists a mix of forest age classes receiving silvicultural treatments (pruning, thinning, fertilization), some are producing logs from thinnings and some from final harvesting for manufacturing processes that produce products, subassemblies and housing developed with known, current technologies and design methods. Owners of relatively new buildings are dealing with relatively minimal upkeep and repair; owners of, say, 15-30 year old buildings, are involved in many maintenance activities using current materials and code requirements; owners of much older homes are dealing with the unique problems they present; and some of the existing housing inventory is being demolished and replaced. The environmental impacts of demolition of today's obsolete homes reflect the actual materials of the past that were used to build and maintain them. This includes problems such as lead-based paints and asbestos that will not be used in future designs but are impacting current disposal and recycling options and will continue to have an impact in the near future.

Summation of activities performed on today's stocks of forest lands and housing, coupled with today's processing, construction, and demolition and disposal methods, provides a more realistic "bottom line" inventory report on the current status of resource and energy consumption and releases to the environment. Furthermore, empirical data can be collected on each of these activities because they are occurring now. Thus all data is empirical in the true spirit of a life-cycle inventory. Similarly, it is relatively easy to collect data on current costs of labor, capital, raw materials (both virgin and recycled) and energy associated with each activity and on market prices for products and develop benefit/cost information. CORRIM has adopted this perspective and used data gathered from current technologies that are applied to currently existing forest and housing cohorts. This means that CORRIM associates data from activities in current nursery, stand initiation, early-, middle, and mature stand cohorts to the current volume of timber extracted. Similarly, occupation and use and demolition data from activities in current housing is associated with the new building structures.

Time = 0
N
P
PTF
PTF’
M
S/S
Y
M
O
D

========

LCI
B/C

Figure 2.5 Simultaneous Cohorts in the CORRIM Life-Cycle System
Note: See Figure 2.4 for definition of symbols

2.7 Scenario Analyses: Policy Changes and Economic Linkages

If one wishes to study the effect of a policy change, such as lengthening forest rotation cycles to store additional carbon, this can be easily accommodated with the cohort approach. Implementing such a policy would alter forest practices whereby each of today’s age classes in Figure 2.5 initiates a process where that class evolves over time in response to practices that would implement the policy (Figure 2.6). Thus, the young stands that were just thinned and fertilized in the present will evolve toward maturity over time under the influence of this policy.

				N=>
			N=>	***P=>***
		N=>	***P=>***	***PTF=>***
	N=>	***P=>***	***PTF=>***	***PTF'=>***
N=>	***P=>***	***PTF=>***	***PTF'=>***	***M=>***
P=>	**PTF=>**	**PTF'=>**	**M=>**	**S/S=>**
PTF=>	**PTF'=>**	**M=>**	**S/S=>**	**Y=>**
PTF'=>	**M=>**	**S/S>**	**Y=>**	**M=>**
M=>	**S/S=>**	**Y=>**	**M=>**	**O=>**
S/S=>	**Y=>**	**M=>**	**O=>**	**D**
Y=>	**M=>**	**O=>**	**D**	
M=>	**O=>**	**D**		
O=>	**D**			
D				

0... time..

LCI_0	LCI_1	....	....	LCI_T
B/C_0	B/C_1	....	....	B/C_T

Figure 2.6 Temporal Progression of Cohorts in the CORRIM Life-Cycle
Note: See Figure 2.4 for definition of symbols

Large bold cells represent pathways (left to right) from present age classes of forest lands and housing. Bold italic cells represent pathways based on future plantings after stocks of existing forests are harvested.

At any point in time, the evolving forest yields logs from thinning and final harvest that are processed by industry into products, subassemblies, and houses. The changes in forestry to accommodate the policy may alter the quantity, size, and quality of the logs available to industry thereby forcing changes in processes, products, and designs, which create new homes for occupancy. Concurrently, maintenance, replacement, repair/remodel, and demolition/disposal is continuing on older homes produced in previous periods. Thus the effect of a policy produces changes in the forest which in turn have lagged effects on the characteristics of materials, which later may affect technologies used, products and design. By forecasting these changes to a time of interest in the future and summing the columns for the time periods, one can obtain inventory summaries and summarize the costs, revenues, and other benefits that occur. These "bottom line" summaries can then be compared in terms of change in physical parameters of interest and in terms of economics.

This approach, in which cradle-to-grave aspects of forest products are regarded as simultaneously occurring cohorts, allows analysts to develop a valid life-cycle-inventory status report on the current situation, develop economic measures of the current situation, and then use forecasting techniques and sensitivity analysis to estimate how changes in any system element lead to changes in environmental and economic measures over time.

This perspective provides a means for reconciling difficulties with temporal aspects of life-cycle inventories associated with forestry and housing and provides a means by which the tool of life-cycle inventory can be used in conjunction with the tools of economic analysis. It is also consistent with the approach commonly used by individual firms in applying and combining life-cycle inventory and improvement analysis methods in identifying cost-effective ways to provide products with improved environmental performance.

3.0 Phase II Accomplishments

This section describes in summary form the accomplishments achieved in Phase II to extend the Phase I coverage. A major accomplishment is the extension of primary LCI measures for structural wood products to cover all 4 major supply regions of the US (INW and NE-NC considering both hardwoods and softwoods in Modules A-D as an addition to SE and PNW covered in the Phase I report). In addition, primary LCI measures were developed for the two major non-structural products, particleboard and MDF for US production in Modules F & G. Given the importance of energy used in the resin feedstocks for composite products another major improvement has been the development of LCIs for US produced resins (Module H), which will also support upgrading the LCIs of resins used in the Phase I products. The primary hardwood lumber product LCI was extended to include the production of hardwood flooring, an important secondary product use of hardwoods (Module E). All Phase I LCI data as well as Phase II data was reviewed for consistency and updated as a part of making the data available in the NREL all materials USLCI database http://www.nrel.gov/lci/. A summary of the differences in cradle to gate LCIs across all wood products is provided in Section 4 and Table 7 of the Appendix.

Other accomplishments include life cycle assessments for completed wall and floor assemblies including the breakdown of impacts to the component level making it practical to predict improvements related to material use decisions. Since framing alternatives may only entail substitution of as little as 6% of the mass of a building, and many components are not affected by the choice of framing material a more complete understanding of substitution potential than just looking at comparative impacts at the level of a completed house is critical (Lippke and Edmonds 2006; and Module I). Finally the Phase II research extends the coverage for completed buildings to west coast locations and the substantial impact seismic standards have on environmental burdens in construction (Module J).

The most sensitive landscape scale environmental issue has become the impact of wildfires which can be reduced by both thinning treatments and the speed of implementing treatments with the potential to reduce substantial environmental damage, avoid future costs, and restore forest health and habitat, essentially providing a triple win potential. Module K is devoted to a landscape scale analysis of the impact of management alternatives on fire with the consequent impacts on carbon and forest health.

The two most significant findings from the Phase I research that were reinforced by the Phase II research may be that (1) wood framing resulted in generally reduced environmental burdens relative to steel or concrete framing and (2) that a life cycle perspective is essential because there can be large tradeoffs between the impact on one stage of processing relative to another such as storing carbon in the forest or in products.

From the Phase I findings we could infer from the environmental assessment that the wood design generally results in lower energy and pollution measures. These comparisons were based on processing energy and excluded the impact of carbon stored in wood products, which substantially alters the greenhouse gas emission impacts. While the Phase I report included carbon stores as a separate analysis, protocols for the LCI data for Phase II were modified to include the carbon stored in products as a negative emission based on sustainably managed forests being essentially carbon neutral such that the carbon exported from the forest to products extends the carbon that was first stored in the forest to its ultimate use in products whether structural or a biofuel. While the steel framed Minneapolis house resulted in a 16% increase in Global Warming Potential from processing emissions without including the carbon stored in wood products by including the carbon as a negative emission the steel frame house emissions rose to 120%, a 7 fold increase. Similarly the concrete framed house emissions rose from 26% without including the carbon stored in products to 156% when they are included during the life of the house, a 6 fold increase.

The extended LCI database, e.g. the hardwood and softwood forest resources as well as hardwood and softwood lumber for NE-NC and INW regions; solid hardwood flooring, particleboard, MDF, resins, can now support more comprehensive life cycle assessments both in product coverage and regions than was possible in Phase I.

Extending the regional coverage to the Inland Northwest has also provided the opportunity to evaluate the impact of critical disturbances such as fire. A time series analysis of carbon from the forest into products, including the impact of biofuels and energy substitution via product substitution and the impact of forest treatments on fire and subsequently carbon pools was produced for Inland Northwest forests.

The Forest Resource module stratifies forest management treatments across forest stand types and owner specific management strategies. The combinations were reduced to a single estimate of yield using weighting factors developed for the stratification. The weighting scheme creates a base case for each region. Alternative weights, such as more acres under a higher level of management intensity, produce an alternative case, with a different calculated volume. Relatively modest increases in the intensity of management produced more than 15% volume increases in the NW, SE and INW. The NE-NC region timber is generally underutilized requiring more detailed analysis to reach conclusions on returns to intensification, which was considered beyond the planned scope of effort.

Along with harvested volumes, the study also produces harvesting cost data and air emission estimates related to stand growth and harvesting. Resources used to produce the harvested volume, such as fuel, fertilizer and herbicides, are quantified and their impacts reported in the Environmental Impact Report during the extraction phase of the single family shell construction.

The Forest Resource Module also produces estimates of tree biomass by component. These estimates are used to estimate the standing and removed carbon pool over time. Indices of stand structure and diversity were developed for the Westside of Washington using a landscape approach to forest management as proxies for changing ecological integrity (Phase I Module O). As a consequence of prior regulatory changes and federal land management policies, all scenarios show some restoration of diverse forest structure that had been declining. More intensive management involving thinnings improves restoration on dry INW sites by reducing overly dense stands. Longer rotations enhance old forest structures on more moist forests but at a substantial economic cost. Thinning INW stands reduces fire risk and restores older forest conditions, a benefit to habitat although not specifically analyzed in this report. The impacts on avoiding carbon emissions from fire while capturing more biomass for carbon offsets were considered to be the most important forest impact especially for dry forests with a high risk and where thinnings contribute to restoration of the historical forest structure (Phase II Module K).

Harvested volumes per unit of forestland from each forest resource region are passed on to lumber and other wood product manufacturers in each region. Independent LCIs for each product are developed for each region. Surveys from a sample of mills in each region for each product were compiled at the unit process level (sawing, drying planning, energy production etc.). The unit process approach produces detailed descriptions of activities and the resource used to produce specific outputs. For example, the sawing process involves log sorting and storage, their delivery to debarkers, and bucking to length. The debarked, bucked logs are sawn into rough lumber producing pulp chips, bark and sawdust as co-products. The rough lumber is transported within the mill to stacks for kiln dryer or planer facilities, two additional processes with their corresponding activities. To accomplish the sawing activity maintenance work on equipment and vehicles are also recorded, as well as treatment processes of air, liquids and solid materials. The result of the survey work produced detail information that was then analyzed with the SimaPro life cycle program (PRé 2001). The result of the analysis produces unit factor estimates for one Mbf of planed dry lumber (and comparable units for other products). These unit factor estimates include raw material usage, airborne waterborne and solid emissions, and energy usage.

In contrast to the Phase I report on building use, maintenance and final disposal, the Phase II report focused instead on stages of processing that were expected to be significantly different from Phase I results. In particular, an integrated analysis is provided in this report for INW carbon tracking by sub region and owner specific treatment plans where increasing rates of fire are having a substantial impact (Module K). In addition, an analysis of the impact of West Coast seismic requirements was completed with substantially different results (Module J) than the more easterly locations used in Phase I.

For determining the integrated impacts (cradle to construction gate) the system boundaries become critical. For example, to determine the cradle-to-gate LCI of manufacturing a given product, i.e., plywood, cumulative data is summed for the forest resource Module with the LCI transportation data based on the delivery mileage to the plywood facility, with the plywood LCI manufacturing data. To determine the LCI for a cradle-to-construction scenario, the cumulative data would be determined by summing the cradle-to-gate LCI for all the wood products used in the construction of the house, with the LCI transportation data based on the delivery mileage and mode of transport from the manufacturing facility to the construction site, and then using ATHENA™ software to include the LCI of the non-wood materials used in the construction and the LCI data for the construction activity. The resulting cradle-to-construction LCI can then be used to determine the associated cradle-to-construction LCA. While use maintenance and disposal were not considered in Phase II, end of product life analysis was applied to carbon tracking across all stages of processing since it was not regionally specific. Post product life LCI analysis such as the impact of carbon in the landfill are not derived with equally precise methods and are long term in impact and are considered of less importance although noted in reports involving integration disposal options.

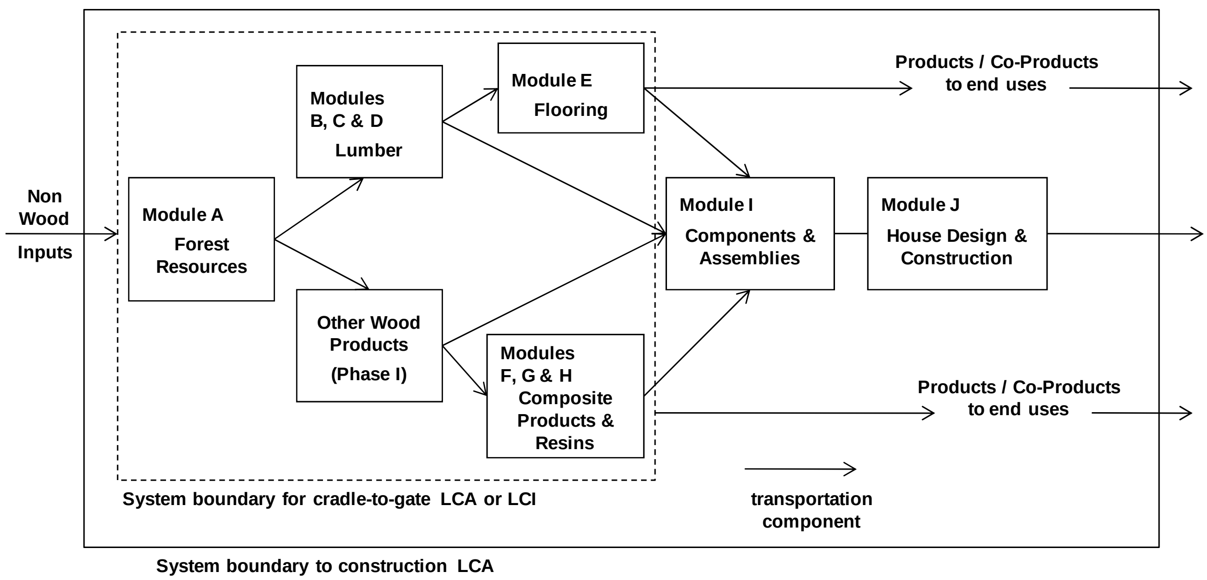

Figure 3.1 System boundaries used to determine various LCI and LCA values based on LCI data in each report Module

4.0 Cradle to production gate LCIs for each product

4.1 Background

Cradle-to-gate life cycle inventories for all products for which life cycle data was developed during the Phase I and II research plans are summarized in Appendix A. Structural products include softwood lumber, hardwood lumber, softwood plywood, OSB, LVL, glue laminated beams and I-joists, with the product LCIs incorporating LCI information for US resins as an important ingredient in laminated products. High volume structural products include hardwood flooring, particleboard, and medium density fiberboard. Product LCIs vary for each major producing region as impacted by the different processing methods used for each species and different energy sources available in each region. Environmental impacts were measured based on emissions to air and water, solid waste, energy consumption, and resource use. Forest product LCIs are somewhat unique in that the measurements for equivalent functional use of a product are based on the volume of the product as different species are used sometimes interchangeably resulting in different densities and processing requirements for functionally equivalent products. LCIs are therefore reported for functionally equivalent products although computations are consistent with mass specific allocations.

4.2 Summary

Results presented in this report might differ slightly from those originally published in the Wood and Fiber Science special publication (Puettmann et al. 2010) and individual product LCI reports (Phase II Modules A-E). Differences in results primarily are a result of fuel database differences used by individual project leaders and those used for the NREL USLCI database. In addition, nonstructural wood panels and associated resins are also presented (Modules F-H) and absent from the original Wood and Fiber Science publication (Puettmann et al. 2010). The cradle-to-gate life cycle stages include forest management and harvesting, transportation, and product manufacturing. The product manufacturing stage consumed the dominant share of energy representing 88% - 93% of the total (Table A4a-A4e). Energy for requirements for forest management and harvesting were low (4-5%) with the higher impacts resulting from areas using the most fertilization. Transportation energy use was also low, about 3-7% of total. Total energy consumption for softwood lumber manufacturing (3,850-4,023 MJ/m^3) was about half of that required for hardwood lumber (6,844) and hardwood flooring (7,315). The use of wood biomass as the primary energy source for manufacturing greatly reduced the environmental burdens by offsetting the demand for fossil fuels. Bioenergy made up as little as 30% of total energy for softwood lumber production Inland Northwest and as much as 71% for SE softwood lumber production. Natural gas provided as much as 47 % of total energy for Inland NW softwood lumber while 4% natural gas was used in softwood lumber production in the NE-NC region. The NE-NC region had the highest usage of coal and crude primarily for electricity generation. Products made with resins generally required more energy. SE OSB (11,000 MJ/m^3) required almost twice as much energy as SE Plywood (5600) and with a much lower share of bioenergy (45% for plywood, 35% for OSB, compared to 71% for lumber).

Total energy consumption for softwood lumber manufacturing (3000 to 3700 MJ/m^3) was about half of that required for hardwood lumber (6000) and hardwood flooring (6700). The use of wood biomass as the primary energy source for manufacturing greatly reduced the environmental burdens by offsetting the demand for fossil fuels. Bioenergy made up as little as 36% of total energy for Inland Northwest lumber and as much as 71% for SE lumber. Natural gas provided as much as 39 to 44% of total energy for PNW and Inland NW lumber while less than 15% for all other products and regions that relied more on coal and oil.
Products made with resins generally required more energy. SE OSB (11000 MJ/m^3) required almost twice as much energy as SE Plywood (5600) and with a much lower share of bioenergy (45% for plywood, 35% for OSB, compared to 71% for lumber).

The growing importance of carbon emissions is generally not a negative consideration for wood products since the carbon stored in the products was removed from the atmosphere (a negative emission) and more than offsets other processing emissions. The carbon stored in wood products substantially exceeds any emissions from processing energy for the life of the product. Product differences result from different species and manufacturing processes, especially use of biofuel instead of fossil fuel. In terms of reduced carbon dioxide equivalent emissions, use of INW softwood lumber results in -686 (kgCO2/cubic meter of wood product used), NE-NC softwood lumber -693, PNW softwood lumber -730, SE softwood lumber -916, and NE-NC hardwood lumber -990.

Results vary after end of useful product life depending upon recycling rates, use of the waste as a fuel source and the degree of emission recapture from the landfill. While none of these can be measured with a comparable degree of precision from a life cycle perspective, of far greater importance is the impact of the use of alternative non-wood products which are more fossil fuel intensive resulting in permanent emissions. A meta analysis of all available studies on substitution noted that 3700 kgCO_2/cubic meter of wood used was the average release when using non-wood substitutes (Sather and O'Connor 2009).

5.0 Reducing Burdens One Component at a Time for Residential Building Floors and Walls

The Phase I Research focused primarily on the impact of framing materials on representative virtual houses in a northern climate (Minneapolis) and a southern climate (Atlanta). While results showed that the processing energy and emissions were generally higher for steel frame relative to wood frame in Minneapolis and concrete block walls vs. wood walls in Atlanta, aggregate comparison for completed houses did not provide adequate direction on how to think about making incremental improvements such as reducing greenhouse gas emissions as an important Global Warming Potential LCA index. By analyzing the impacts at the level of components and those components most critical in structural assemblies, strategies for environmental improvement become more obvious. (Lippke and Edmonds 2006, also Module I this report).

As noted in Figure 5.1, the wood floor-joist ***components*** that are used in the construction of floors (dimension wood joist {Dim-Joist} and Engineered Wood I-Joists {EWP I-Joist} both store carbon (negative emissions) as their emissions from processing are more than offset by the carbon removed from a sustainably managed carbon neutral forest that becomes carbon stored in the products. In contrast, the non-wood Concrete Slab and Steel Joists result in substantial carbon emissions (2-4 kgCO_2/sq ft of floor). Adding a wood covering (plywood {Ply} or oriented strandboard {OSB}) to steel joists for a ***floor-assembly*** does not offset the emissions from the heavy gauge steel that is used in flooring. EWP I-joists with wood covering store less carbon than dimension joists because they use less fiber but all combinations of wood joist and wood covering store substantial amounts of carbon compared to non-wood joists and floor covering which result in significant emissions.

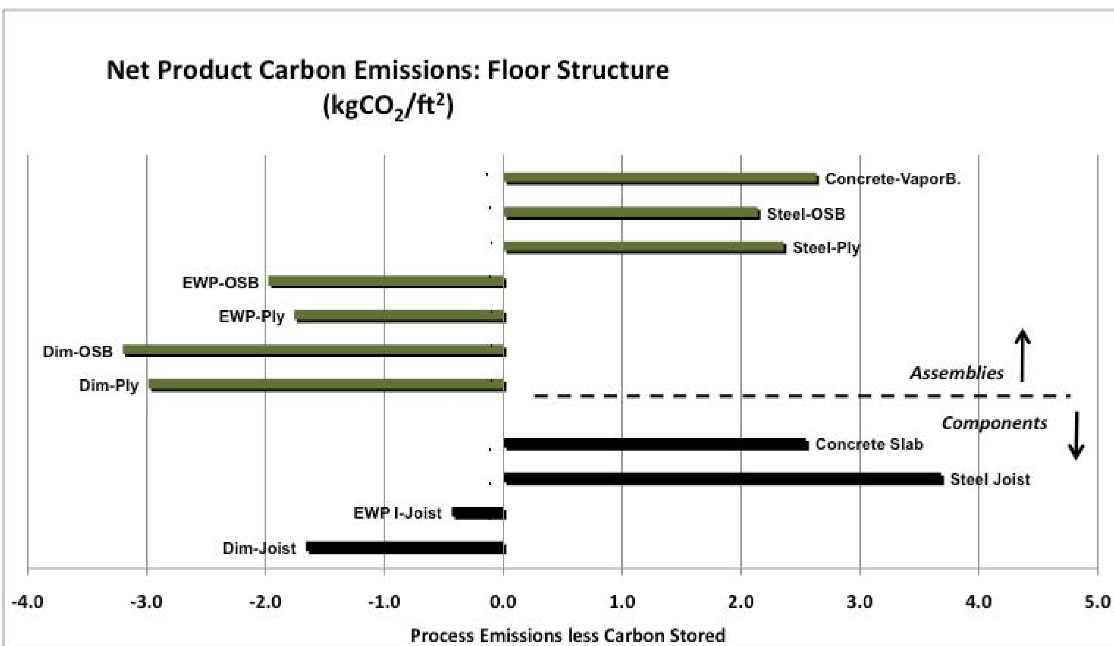

Figure 5.1 Process Emissions less Carbon Stored in Floor Structure Components and Assemblies
(source: Appendix Module I)

The EWP I-joist with an OSB cover is substantially better than a concrete slab reducing GWP emissions by 3 kg per sq. ft. of floor. Another measure of interest is the emission reduction relative to the fiber used as an efficiency of substitution measure. The EWP I-joist reduces CO_2 emissions by 4.6 kg per kg (dry weight) of wood used. The comparison with steel joists and OSB cover reduces emissions by 9.8 kg per sq. ft., more than twice as effective as the substitution for a concrete floor largely because steel joists must be heavy gauge to minimize floor bounce resulting in substantial processing emissions, a relatively poor application for steel. But since the steel floor also uses wood in the floor cover as a partial carbon offset it is less fiber efficient reducing emissions to 4.2 kg per kg of wood used, slightly less than by displacing concrete flooring. If there is an adequate supply of wood, greater use of wood will improve the carbon footprint in structures the most. If not, efficient use of fiber becomes important.

While displacing steel in floors by wood is more effective than displacing concrete these findings cannot be generalized to wall assemblies. As noted in figure 2, the wood-wall ***components*** (kiln dried stud {KDStud}, Plywood, OSB, biofuel dried plywood {BioDryPly}) all store carbon more than offsetting their processing emissions, and some ***wall assemblies*** use sufficient amounts of wood to more than offset the emissions of some non-wood components such as the emissions from the use of vinyl cladding. As a component, concrete block substitutes not only for wood studs, but also the wood sheathing and with the addition of a stucco cladding for any wood or vinyl cladding used with wood framed walls. The best configurations use wood products with biofuel used for drying. The assembly made of biofuel-dried-studs, biofuel-dried-plywood in both sheathing and cladding stores the most net carbon with the use of OSB sheathing almost as good.

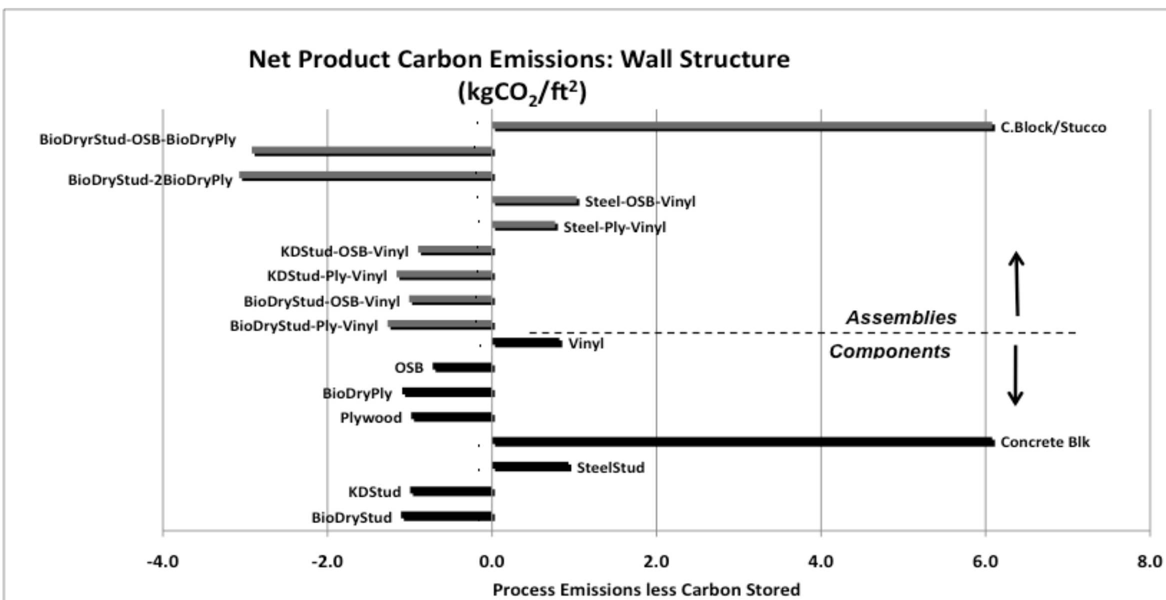

Figure 5.2 Process Emissions less Carbon Stored for Wall Components and Assemblies

The biofuel dried stud with biofuel dried plywood sheathing and cladding substitution for the more conventional kiln dried stud with OSB sheathing and vinyl siding reduces GWP by over 2.2 $kgCO_2$ per sq. ft. of wall with a fiber efficiency of 2.1 kg CO_2 reduction per 1kg of fiber used (top bars). The benefit of this within wood substitution is almost the same as replacing a conventional steel wall assembly with a conventional wood assembly, which involves no increased use of biofuel in drying. By doing both, increasing the use of biofuel and substituting for a steel framed wall assembly, GWP emissions are reduced by 4.1 $kgCO_2$ per sq. ft. of wall with a fiber substitution efficiency of 2.7 $kgCO_2$ per kg of wood fiber used.

Using the wood designs compared to a concrete and stucco wall result in GWP reductions of 7-9 $kgCO_2$ per sq. ft. of wall or almost 3.5 $kgCO_2$ per 1 kg use of fiber. While the wood is more effective at displacing the emissions from steel in floors and concrete in walls the displacement of emissions per unit of wood fiber used is not as different. The use of more fiber is a substantial part of the opportunity for improvements but may not provide the high leverage that is provided by critical component comparisons such as steel joists vs. EWP I-joist. Using more fiber as biofuel in products helps to reduce the GWP in structural assemblies by reducing fossil fuel emissions in processing but will not likely be as efficient as using fiber for structural components. It still may be the best use of low quality fiber not suitable for engineering into structural components. However, different components do perform better in different applications and these differences are not generally identified or valued in current market exchanges. This sampling of materials and designs is not exhaustive but suggests many design, product and process changes that can improve environmental performance. The most obvious include (1) using a renewable wood resource instead of a fossil intensive resource and especially where the substitution advantage is large, (2) using biofuels to reduce the fossil fuel use in manufacturing wood, (3) using resource efficient materials pre-cut to length or pre-assembled units and (4) using recycled materials that require less energy. The results also suggest the potential for many future improvements in the design of components that can displace the higher energy components and the design of new pre-assembled units that can gain several of these advantages at once.

6.0 Seismic Code Considerations

6.1 Introduction

Much of CORRIM's work to date has focused on alternative material designs for residential single family housing in the continental US (e.g. Minneapolis and Atlanta). Considerable effort went into ensuring that these alternative structural material residential designs (wood, steel and concrete) were functional equivalent and relevant to their regional location. In Module J, the impact of seismic codes is evaluated – specifically for Los Angeles and Seattle, as these two locations are representative of areas with relatively high seismic activity and loadings. These seismic loadings in turn result in the use of a number of additional structural materials and systems to satisfy local codes. Seismic codes like other building codes are locally controlled and subject to change but the relative magnitudes of the impacts on environmental burdens trace directly from the objectives of the codes to withstand earthquakes with minimal damage.

6.2 Approach

Previous alternative design comparisons conducted by CORRIM were completed using the Athena Institute's Impact Estimator software for buildings. The software supports cradle-to-grave life cycle assessment of whole buildings in various regions of N. America. The software incorporates material quantity take-offs for various structural and envelope materials and assemblies and summarizes a building's environmental profile using a set of six life cycle impact assessment measures or indicators. In keeping with the use of the Impact Estimator for buildings software, quantities of materials related to seismic requirements were defined based on either an incremental percentage increase of existing materials, or as a materials list where additional new materials are required. A variety of assembly systems within the Impact Estimator's software were considered for single-family houses, row housing, and low-rise commercial buildings in the two seismic building locations. Module J provides general findings and then concentrates on single-family house seismic requirements and their environmental life cycle implications across two alternative material designs (wood and steel).

Seismic base shear values were calculated to develop seismic requirements across various material assembly types. Seismic base shear calculations for both Seattle and Los Angeles were calculated using the 2003 International Building Code (IBC 2003) and ASCE-7-02 Minimum Design Loads for Buildings as referenced by IBC 2003.

The seismic requirements for lateral load resisting wall systems will vary depending on the height and mass of a building and the structural framing configuration. The requirements will also vary dependent on soil conditions and proximity to active faults. In evaluating the seismic requirements for the wall systems it was necessary to make assumptions as to the soil conditions, proximity to fault lines, and the type of building each wall system will be typically used in.

Using similar wood and steel structural designs for a single-family home modeled in Minneapolis, Seattle and Los Angeles the influence of incrementally greater seismic reinforcement is calculated in terms of embodied primary energy, global warming potential (GWP), air and water pollution and solid waste effects. Results indicate that seismic requirements significantly increase the environmental footprint of residential structures, ranging from an increase of 60 to 100% for energy, GWP and air pollution. The increases from meeting the seismic codes are similar across both wood and steel designs with the percentage increase for a wood design slightly larger than the impact of substituting a steel frame for a wood frame without an increase in seismic requirements. In essence, the impact of seismic codes is as great as substituting steel framing for wood framing. A better understanding of these impacts should motivate design changes and material use changes as opportunities to lower the environmental impacts of buildings in areas with seismic requirements.

7.0 Integrated Life Cycle Assessment of Carbon from Cradle to Product Uses and Substitution including the Impact of Fire on Inland Forests

7.1 Introduction

Carbon emissions and stores are impacted by plant growth as well as just about every manufacturing process adding complexity to the challenge of keeping track of net impacts. The carbon equivalent metric for greenhouse gases is useful for comparing emissions from manufacturing processing, fossil fuel use, and wildfire to the carbon dioxide taken up and stored in forests, and the wood products that are made from trees. Life cycle inventory measures of current technology processes provide a cross section of carbon impacts for each stage of processing that can be identified with each point in time starting with forest regeneration, then harvesting/processing, and ultimately the use of the products, their impact on substitutes, and end of life impacts (Module N Phase I Final Report). Carbon tracking across these many carbon pools provides a comprehensive demonstration of the range of impacts any one action can have on carbon mitigation.

7.2 Carbon Tracking Across Carbon Pools for a Single Stand

We summarize here the impact of sustainably managing a typical Pacific Northwest (PNW) private forest stand using a single hectare example as developed in Perez-Garcia et al (2005). Figure 7.1 characterizes the impact of private forest management in the Pacific Northwest for the primary linked carbon pools, (1) the forest, (2) short and long lived products with deductions for the emissions from processing energy, (3) the displacement of fossil emissions from the energy generated by residual biomass, and (4) substitution for fossil intensive products displacing their emissions, such as the substitution of wood framed walls for concrete shown in the figure. Forest carbon neutrality is not assumed but a stable long-term trend in forest carbon is effectively demonstrated under sustainable management.

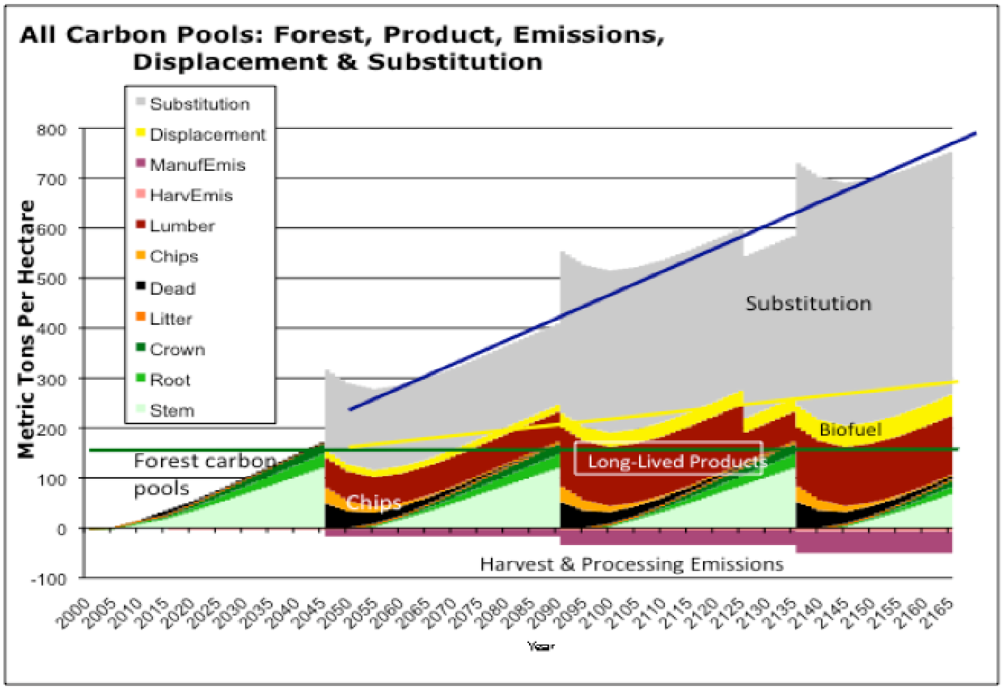

Figure 7.1 All Carbon Pools

For the PNW private forest, carbon across all pools grows sustainably at about 5 tonnes C/hectare/yr (t C/h/yr) based on growth model simulations with 45 year rotations. No credit is shown for carbon stored in the landfill for either short or long-lived products, providing an ultra conservative estimate of carbon mitigation. No soil carbon is shown based on research suggesting soil carbon remains stable under sustainable forest management (Johnson and Curtis 1991) although it can increase with fertilization (Adams et al 2005) or be substantially reduced with wildfire (Bormann et al 2008).

7.3 Carbon in Older Forests

Generally the amount of carbon stored in a young forest is less than the amount stored in an old forest for a given locale and site quality. For example, figure 7.2 summarizes the tree carbon by stand age based on FIA data from USFS stands for Western Washington, which provide a large sample of inventory for older ages. Even though select old forest stands are renowned for their longevity, net growth across all old forest stands and hence net carbon accumulation ceases soon after 100 years as mortality offsets new growth.

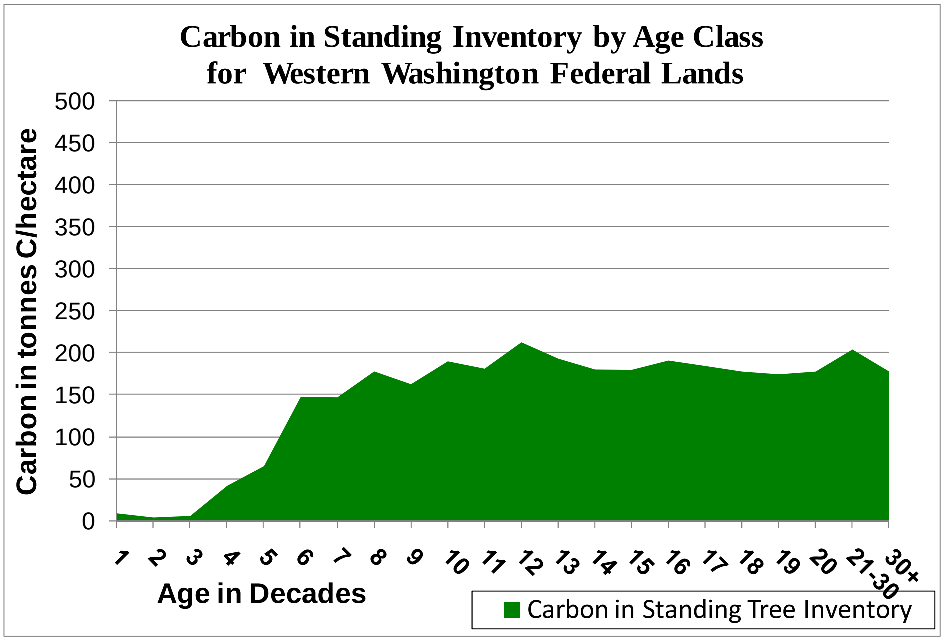

Figure 7.2 Stored Tree Carbon versus Age of Stand

A comparison of Figures 7.1 and 7.2 suggests that there are better alternatives for maximizing carbon dioxide mitigation than using the forest as a storage facility. A much greater carbon sequestration benefit can be obtained if we use the forest as a carbon pump to store carbon in products. In the pump analogy, the forest pulls carbon dioxide from the atmosphere via photosynthesis, converts the carbon dioxide to a solid (which we measure in units of carbon) that can then be moved (i.e. pumped) from the forest to other carbon storage pools like solid wood products that store carbon for a long time. There is even a benefit if the wood is burned to offset fossil fuel usage though it is not as great as first storing the carbon in solid wood products. The efficiency of the pump is determined by both the rotation length and the efficiency in product use. If forests are harvested before the maximum rate of growth slows down, the forest pump operates at high efficiency. If harvest is delayed past the point of maximum growth rate, then efficiency declines, sometimes rapidly depending on the species and site conditions. A comparison of figures 7.1 and 7.2 shows the substantial carbon sequestration gains that can be obtained by managing forests for a sustainable harvest over time relative to leaving them unharvested even in places where natural disturbance does not have a dominant impact. Under accelerated disturbance regimes driven by climate change and a century of fire suppression, opportunities to save as much of the carbon in the forest as possible for useful purposes whether in wood products or biofuels will likely provide more carbon mitigation than expecting further carbon accumulation in the forest.

7.4 Landscape Carbon for the Inland Northwest region

The Inland Northwest (INW) forests have a much different character than the Pacific Northwest forests displayed in Figures 7.1 and 7.2. The forests themselves are quite variable in terms of productivity, species composition, and disturbance regime; the ownership patterns and management regimes are just as disparate, and in the past decade, disturbances, especially fire and insects, are emerging as a dramatic player in the natural carbon storage and release cycle in this region.

For the INW state and private landscape treatments like that demonstrated above were stratified across the INW FIA plots, first for State and Private based on historic harvest rates over the last three decades thereby scaling the impact up to the total landscape. The average hectare is used to provide a representative sample for the region (Module K this report). The results include carbon stored in the forest, in products, displacement of fossil emissions when used as a biofuel in processing, and substitution for fossil intensive products that permanently displace their emissions. Since the product carbon pools are initiated at a point in time, the history of carbon from prior harvesting is excluded. Stratifying management treatments across forest types to the entire Inland Northwest landscape provides a useful measure of carbon mitigation potential and how it depends on regional land productivity, potential natural disturbances and owner specific management objectives.

Simulations show private management regimes are nearly maximizing sustainable harvest removals and their use as structural materials (Figure 7.3a) on a landscape level basis. Landscape level forest carbon under State and Private management for the average hectare is almost in a steady state equilibrium. There is little accumulation in short lived products (outside of landfills), but a sustainable increase in long lived product carbon and substitution pools. The average for carbon across all pools grows sustainably at about 2.7 tC/h/yr reflecting the lower productivity of Inland forests relative to the Pacific Northwest forests shown in figure 7.1.

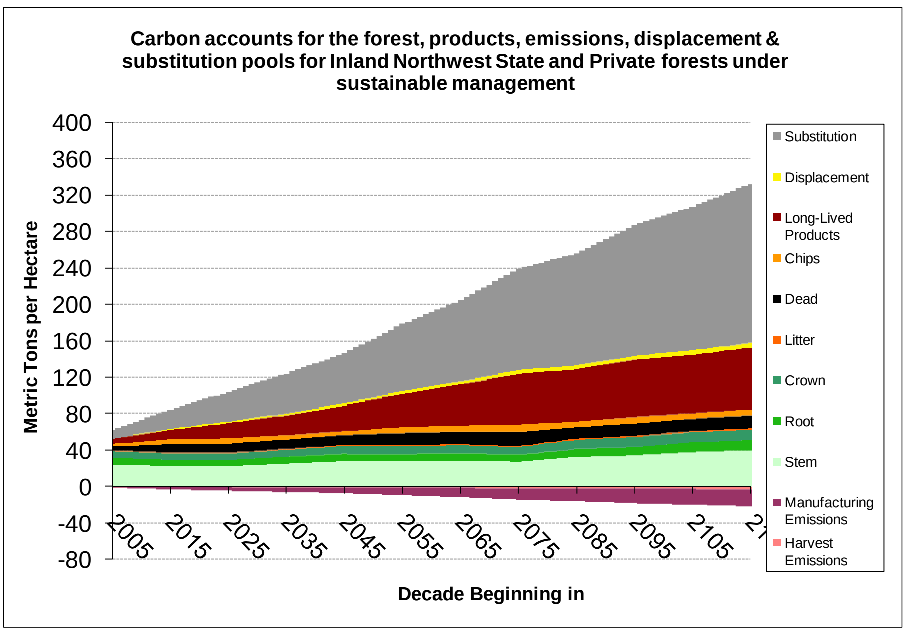

Figure 7.3a Landscape carbon accumulation for Inland Northwest state and private forests

On federal lands, a century of fire suppression has resulted in overly dense stands that, on average, carry almost twice as much biomass and therefore twice as much carbon as state and private forests at the current time. The limited ecosystem restoration activities occurring on federal lands although designed to reduce fire risks convert relatively low volumes into product carbon stores and offsets and may not be sufficient to effectively reduce fire and hence this regime most likely overstates forest carbon growth (Figure 7.3b).

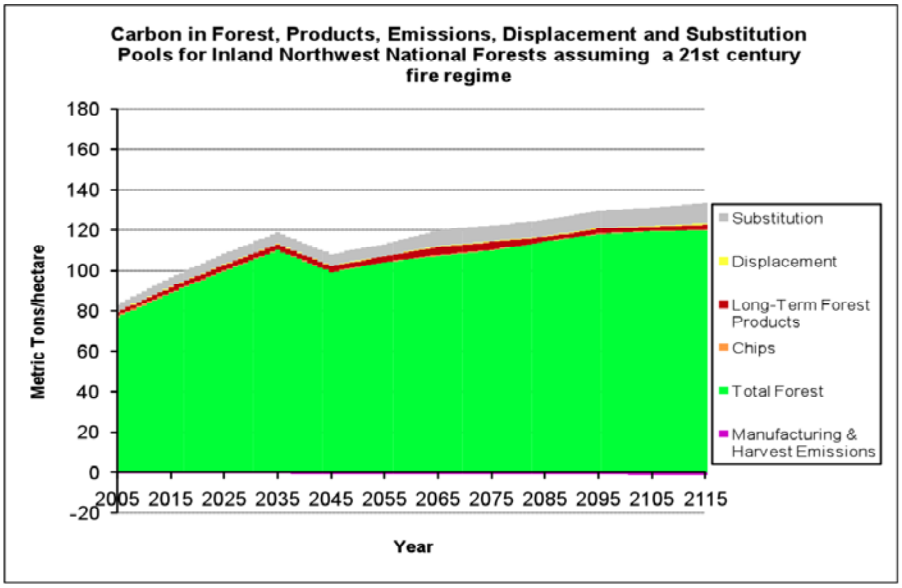

Figure 7.3b Landscape carbon accumulation for Inland Northwest national forests

Simulations of a fourfold increase in restoration thinning treatments (not shown) designed to better reduce the fire risk on dry and moist forests could capture close to half the potential carbon storage projected for state and private management.

7.5 The Impact of Increasing Fire Rates

The relative percentage of acres burned is substantially higher on Federal forests as compared to state or private forests and the fire rate has increased dramatically in recent years most likely driven by climate change. The stochastic nature of fire coupled with dynamic feedbacks and external variables such as climate change and fire suppression makes projecting fire rates difficult. A range of fire treatments and carbon impacts were simulated in Module K (this report) suggesting that with no treatments and a continuation of recent fire rates, the Inland Federal Forests may well become a source of emissions rather than a sink.

Figure 7.4 shows the range of carbon estimates for federal forests using five different fire rate scenarios based on the literature and recent fire history reports.

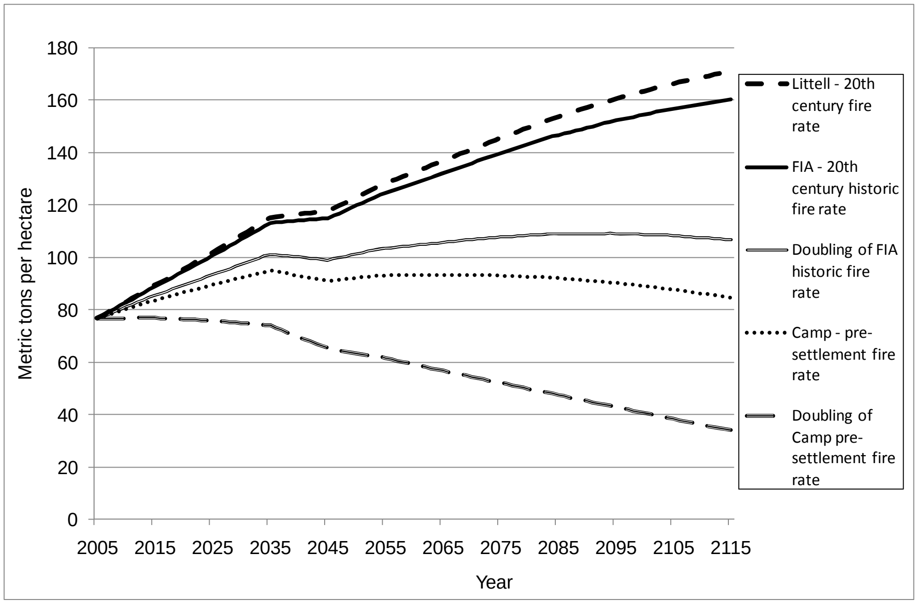

Figure 7.4 Potential landscape carbon accumulation for INW national forests under 5 fire rate assumptions.

While Figure 7.3.b includes an estimate of the predicted impacts of future climate based on a doubling of the 20th century rate, it still predicts approximately 40% more carbon would remain on the landscape in 50 years than would occur using the fire rate from 2002-2009. While thin from below strategies designed to restore an old forest overstory can reduce risk, the increase in average area burned by wildfire in the Inland Northwest absent an increase in effective fire risk reduction treatments will likely continue resulting in increased forest carbon emissions. The increasing fire risk has already resulted in reduced opportunities to store carbon in wood products and to displace fossil intensive products like steel and concrete.

7.6 Summary of Impacts

Figure 7.5 summarizes this wide range of carbon impacts from essentially no increase (or a potential decrease) in carbon stored on untreated federal lands to the sustainable accumulation of carbon stores across all pools for sustainably managed state and private forests.

Management on State and Private Inland Northwest forests can sequester or avoid emissions equal to 294 t/ha of carbon in 100 years, which equals over 1.9 billion t of carbon across 6.5 million ha of Inland forests under current harvest conditions. Seventy nine percent of the carbon accumulates beyond current forest carbon inventories. On National Forests carbon sequestration and avoided emissions for accelerated thinnings are 152 t/ha over 11 million ha of unreserved forests for 1.6 billion t of carbon stored.

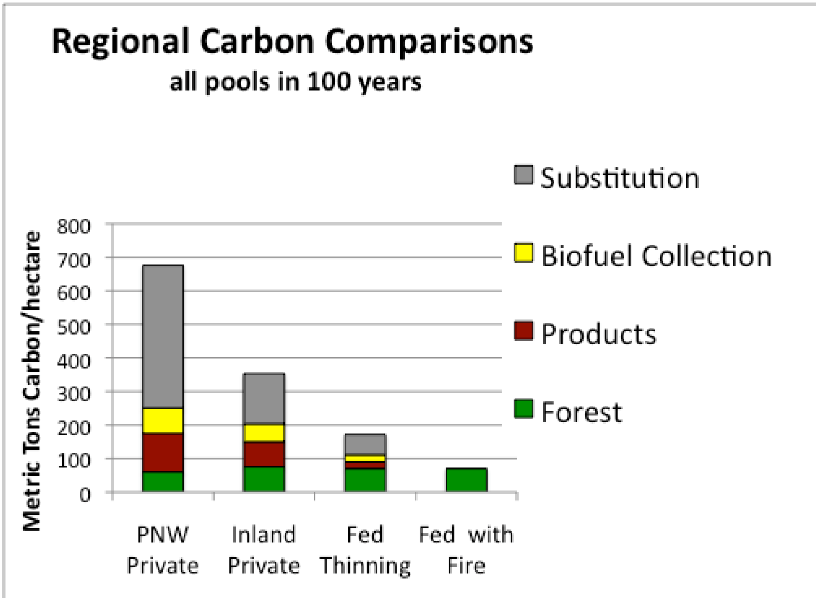

Figure 7.5 Region/owner specific Carbon across all pools

The cumulative carbon emission reduction varies widely depending upon regional soil productivity and treatment, with these differences likely being sensitive to climate change. State and Private Inland forests are expected to increase carbon stores 2.7 t C/h/yr compared to over 5 t/C/h/yr for Westside forests under similar management regimes. Current Federal management is unlikely to show any increase in carbon stores and may contribute net emissions whereas a 400% increase thinnings to reduce fire risks while still retaining an old forest overstory could increase stores almost 1t C/ha/yr (or perhaps more with more aggressive proportional thinning treatments).

Life cycle analysis suggests that the optimal solution for maximizing carbon gain is to manage forests to maximize long-lived wood products and to minimize the risk of severe wildfires. Increased biofuel collection of currently unused forest residuals and thinnings provides a future opportunity although dependent upon improved economics. The carbon storage in buildings and the substitution benefits override the potential gains of attempting to leave high carbon stocks stored in the forest particularly in the Inland Northwest forests, where wildfire disturbance is emerging as a dominant carbon release mechanism.

8.0 Environmental Improvement Opportunities

Many opportunities for environmental improvement have been noted including forest management, process and material substitution. There may of course be internal tradeoffs between environmental burdens with some rising while others fall. There may also be cost tradeoffs that need to take into consideration the time value of money. The report identifies many areas where environmental performance improvement is possible. Those opportunities that would appear to have a substantial improvement potential and benefit from further analysis using the LCI information in this report include:

- Redesign of the house to use less fossil intensive products
- Redesign of the house to reduce energy use (both active and passive)
- Redesign of the codes that result in inefficient and excessive use of wood and concrete

- Greater use of low valued wood fiber for biofuel
- Greater use of engineered products producing higher valued products from less desirable species.
- Improved process efficiencies such as the boiler or dryer (including air drying)
- Environmental pollution control improvements based on LCI/LCA
- More intensive forest management
- Recycling demolition wastes
- Increased product durability (given the already long expected life of a house, from 75-100years, this applies primarily to moisture/weather exposed areas).
- Using more wood to meet seismic standards
- Recognition that life cycle analysis is essential to measure improvement across all stages of processing as tradeoffs exist across the system, and that policy or investment decisions focusing on only one stage of processing or carbon pool may be counterproductive.
- Product development focused on reducing the environmental footprint along with product life.

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Appendix A: LCI's for Wood Product Production Processes

Table A1 CORRIM Phase I and Phase II LCI processes. The process data are available through the US LCI database (NREL 2009)

CORRIM LCI Processes Collected from Industry Surveys					
	CORRIM Phase I		**CORRIM Phase II**		
	Pacific Northwest	**Southeast**	**Inland Northwest**	**Northeast-Northcentral**	**CORRIM Report**
Forestry operations	1. Seedling growth, 2. Management, 3. Equipment, 4. Final harvest	1. Seedling growth, 2. Management, 3. Equipment, 4. Final harvest	1. Seedling growth, 2. Management, 3. Equipment, 4. Final harvest	1. Management, 2. Equipment, 3. Final harvest	Johnson et al. 2004, 2008; Oneil et al. 2009
Wood Products					
Lumber, softwood	1. Sawing, 2. Drying, 3. Boiler, 4. Planing	1. Sawing, 2. Drying, 3. Boiler, 4. Planing	1. Log yard 2. Sawing, 3. Drying 4. Boiler, 5. Planing	1. Log yard 2. Sawing, 3. Drying 4. Boiler, 5. Planing	Wagner et al. 2009; Bergmann and Bowe 2008
Lumber, hardwood				1. Log yard 2. Sawing, 3. Drying, 4. Boiler, 5. Planing	Bergmann and Bowe 2008
Flooring, hardwood				1. solid strip hardwood flooring	Hubbard and Bowe, 2009
Plywood, softwood	1. Debarking, 2. Conditioning, 3. Peeling/clipping, 4. Drying, 5. Layup/pressing 6. trimming/sawing 7. Boiler	1. Debarking, 2. Conditioning, 3. Peeling/clipping, 4. Drying, 5. Layup/pressing 6. Trimming/sawing 7. Boiler			Sakimoto and Wilson, 2004
Laminated veneer lumber (LVL), softwood	1. LVL	1. LVL			Dancer and Wilson, 2004
Glued laminated beams (glulam), softwood	1. Glulam production, 2. Boiler	1. Glulam production, 2. Boiler			Puettmann and Wilson, 2004
I-Joist, softwood	1. I-joist production	1. I-joist production,			Dancer and Wilson, 2004

CORRIM LCI Processes Collected from Industry Surveys					
	CORRIM Phase I		CORRIM Phase II		
	Pacific Northwest	Southeast	Inland Northwest	Northeast-Northcentral	CORRIM Report
Oriented strandboard (OSB), softwood		1. Log handling/ flaking, 2. Drying/screening, 3. Blending/pressing, 4. Sanding/sawing, 5. Boiler, 6. Emissions control			Kline, 2004
			CORRIM Phase II		
			US Average Process		**CORRIM Report**
Particle board			1. Particleboard		Wilson 2008
Medium density fiberboard			1. Medium density fiberboard		Wilson 2008
Urea formaldehyde resin			1. Urea formaldehyde resin		Wilson 2009
Melamine urea formaldehyde resin			1. Melamine formaldehyde resin		Wilson 2009
Phenol formaldehyde resin			1. Phenol formaldehyde resin		Wilson 2009
Phenol resorcinol formaldehyde resin			1. phenol resorcinol formaldehyde resin		Wilson 2009

Table A2 Biomass input data for the cradle-to-gate LCI analysis. Data are allocated to final product, no co-products included. (Updated from publication ~~1~~).

	Harvesting				Transportation[1]				Manufacturing		
Final product	**Logs[2]**	**Logs[3]**	**Bark**		**Logs**	**Bark**	**Lumber**		**Planed dry lumber**	**Rough dry lumber**	**Solid strip flooring**
	m^3	kg	kg		tkm				m^3	m^3	m^3
Inland NW softwood lumber (INW)	1.11	455	34		94	7	-		1 (=436 kg)	-	-
NE-NC softwood lumber	1.08	389	54		84	11	-		1 (=420 kg)	-	-
NE-NC hardwood lumber	1.32	594	130		141	16	-		1 (=572 kg)	-	-
NE-NC hardwood solid strip flooring	1.39	626	136		148	17	211		-	1.05	1

[1] Transport (one-way): INW=129 km; NE-NC softwood = 109 km; NE-NC hardwood = 125 km; Solid Strip Flooring = 125 km

[2]Green volume measured without bark. Moisture content: INW = 60%; NE-NC softwood 97%; NE-NC hardwood = 87%; Solid Strip Flooring = 87%

[3]Oven dry mass. Using green specific gravity (oven dry mass, green volume): INW = 0.41; NE-NC softwood 0.36; NE-NC hardwood = 0.45; Solid Strip Flooring = 0.45

Table A3 Annual production reported in primary surveys from the Inland Northwest and the Northeast-Northcentral United States

Wood product		**Production from survey manufacturers**		**% of regions production[1]**
Northeast-Northcentral	**Unit**			
Softwood lumber	m^3	531,000	(256 MBF)	12
Hardwood lumber	m^3	784,000	(301 MBF)	6
Hardwood flooring	m^2	12,425,000	(134 Mft^2)	28[2]
Inland Northwest				
Softwood lumber	m^3	755,852	(466 MBF)	16

[1] Bergmann and Bowe 2008a, 2008b; Hubbard and Bowe 2008; Wagner et al. 2009).

[2] Percent of total U.S. solid-strip flooring production

Table A4a ***Softwood lumber - Inland Northwest region*****: Cradle-to-gate cumulative energy (MJ/m^3) by fuel source allocated to 1.0 m^3 of product for each life cycle stage. (Updated from publication ~~1~~)**

Electricity production and transportation of raw materials to wood manufacture facilities are included.

	Harvesting	Product Manufacturing	Transportation	Total	Percentage of total
Coal	5.55	309.65	3.61	318.82	8%
Crude	151.65	123.68	117.68	393.01	10%
Natural gas	10.82	1,787.34	7.74	1,805.90	47%
Uranium	1.90	99.95	1.25	103.10	3%
Biomass	0.00	1,153.68	0.00	1,153.68	30%
Energy from hydro	0.00	69.10	0.00	69.10	2%
Other energy sources	0.00	6.51	0.00	6.51	<1%
Total	169.93	3,552.99	130.27	3,853.19	100%
Percentage of total	4%	92%	3%	100%	

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

Table A4b ***Softwood Lumber – Northeast-Northcentral regions*****: Cradle-to-gate cumulative energy (MJ/m^3) by fuel source allocated to 1.0 m^3 of product for each life cycle stage. (Updated from publication ~~1~~)**

Electricity production and transportation of raw materials to wood manufacture facilities are included.

	Harvesting	Product Manufacturing	Transportation	Total	Percentage of Total
Coal	6.05	466.36	3.39	475.80	12%
Crude	197.23	432.37	110.61	740.20	18%
Natural gas	12.96	134.72	7.27	154.95	4%
Uranium	2.09	166.65	1.17	169.92	4%
Biomass	0.00	2,475.53	0.00	2,475.53	62%
Energy from hydro	0.00	5.89	0.00	5.89	0%
Other energy sources	0.00	1.08	0.00	1.08	0%
Total	218.34	3682.61	122.44	4023.38	100%
Percentage of Total	**5%**	**92%**	**3%**	**100%**	

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

Table A4c ***Hardwood Lumber – Northeast-Northcentral regions:*** **Cradle-to-gate cumulative energy (MJ/m3)by fuel source allocated to 1.0 m3 of product for each life cycle stage. (Updated from publication 1)**
Electricity production and transportation of raw materials to wood manufacture facilities are included.

	Harvesting	Product Manufacturing	Transportation	Total	Percentage of Total
Coal	7.81	997.39	5.62	1010.82	15%
Crude	254.79	379.88	183.41	818.08	12%
Natural gas	16.75	951.25	12.06	980.05	14%
Uranium	2.70	355.82	1.95	360.47	5%
Biomass	0.00	3659.89	0.00	3659.89	53%
Energy from Hydro	0.00	12.75	0.00	12.75	<1%
Other energy sources	0.00	2.35	0.00	2.35	0%
Total	282.05	6359.33	203.03	6844.41	100%
Percentage of Total	4%	93%	3%	100%	

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

Table A4d ***Solid- strip Hardwood Flooring – Northeast-Northcentral regions:*** **Cradle-to-gate cumulative energy (MJ/m3)by fuel source allocated to 1 m3 of product for unit each life cycle stage for. (Updated from publication ~~1~~)**
Electricity production and transportation of raw materials to wood manufacture facilities are included.

		Product manufacturing				
	Harvesting	Hardwood Lumber	Hardwood flooring	Transportation	Total	Percentage of total
Coal	1.19	7.03	748.67	58.77	815.65	11%
Crude	268.05	326.85	10.91	438.69	1,044.50	14%
Natural gas	17.62	926.44	39.33	28.84	1,012.23	14%
Uranium	2.85	267.18	20.94	4.66	295.63	4%
Biomass	0.00	3,837.57	297.06	0.00	4,134.63	57%
Energy from Hydro	0.00	9.54	0.76	0.00	10.30	0%
Other energy sources	0.00	1.75	0.14	0.00	1.89	0%
Total	289.70	5,376.36	1,117.83	530.95	7,314.83	100%
Percentage of total	4%	73%	15%	7%	100%	

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

Table A5 ***Regional Wood Product Processing Comparisons by Fuel Source:*** **Cradle-to-gate cumulative energy2 requirements by fuel source (MJ/m3) allocated to one cubic meter of product (Pacific Northwest, Southeast, Inland Northwest and Northeast-Northcentral (NE-NC) regions).**

Electricity production and transportation of raw materials to the wood manufacturing facilities are included. (updated from publication1).

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring[3]
	PNW	SE	Inland NW	NE-NC	NE-NC	NE-NC
Coal	92	356	319	476	1011	816
Crude oil	361	337	393	740	818	1,045
Natural gas	1,447	279	1,806	155	980	1,012
Uranium	7	35	103	170	361	296
Biomass	1,595	2,475	1,154	2,476	3,660	4,135
Energy from hydro	200	4	69	6	13	10
Other energy sources	3	8	7	1	2	2
TOTAL	3,705	3,492	3,853	4,023	6,844	7,315

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

[2] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, diesel 44.0, liquid propane gas 54.0, natural gas 54.4, crude oil 45.5, oven dry biomass 20.9, and gasoline 48.4. Energy from uranium was determined at 381,000 MJ/kg.

[3] Includes the cradle-to-gate production of rough dried hardwood lumber to produce 1 cubic meter of hardwood flooring.

Table A6 ***Regional Wood Product Energy Comparisons by Stage of Processing:*** **Cradle-to-gate, cumulative energy2 (MJ/m3) allocated to one cubic meter of product manufactured in the Pacific Northwest (PNW), Southeast (SE), Inland Northwest, and Northeast-Northcentral regions.** (updated from publication1).

Electricity production and transportation of raw materials to the wood manufacturing facilities are included.

	CORRIM Phase I[3]		**CORRIM Phase II**			
	Softwood lumber		**Softwood lumber**		**Hardwood lumber**	**Hardwood flooring**
	PNW	**SE**	**Inland NW**	**NE-NC**	**NE-NC**	**NE-NC**
	MJ/m³					
Harvesting	143	203	170	218	283	290
Product Manufacturing	3,415	3,175	3,553	3,683	6,360	6,494[5]
Transportation[4]	147	114	130	122	203	531
TOTAL	3,705	3,492	3,853	4,023	6,844	7,315

[1]Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases uses the Reliable Council electricity grids (www.nrel.uslci.gov).

[2] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, natural gas 54.4, crude oil 45.5, and oven dry wood 20.9. Energy from uranium was determined at 381,000 MJ/kg.

[3] Puettmann and Wilson 2005.

[4] Transportation of raw materials (logs, lumber, fuel, etc.) to the wood manufacturing facilities are included.

[5] Includes hardwood lumber and flooring processes

Table A7 ***Solid Wood Products*****- Biomass, Carbon and CO2 per 1.0 cubic meter of final product.**
All allocated to final product; co-products not considered.

	Softwood lumber								Hardwood lumber		Hardwood Flooring	
	INW		NE-NC		PNW		SE		NE-NC		NE-NC	
	Carbon (kg C/m^3)	kg CO_2/m^3	Carbon (kg C/m^3)	kg CO_2/m^3	Carbon (kg C/m^3)	kg CO_2/m^3	Carbon (kg C/m^3)	kg CO_2/m^3	Carbon (kg C/m^3)	kg CO_2/m^3	Carbon (kg C/m^3)	kg CO_2/m^3
Carbon[1] in biomass (logs) or CO_2 uptake in trees of biomass delivered logs	246	899	242	887	296	1,085	279	1,023	459	1,683	482	1,767
Carbon[1] or CO_2 stored in final product	218	799	214	785	233	854	265	972	315	1,155	361	1,324
Carbon[1] or CO_2 stored in Biofuels[3]	28	103	28	103	46	169	61	224	144	528	121	444
Non biogenic CO_2 processing emissions [4]	31	113	25	92	34	124	15	56	45	165	46	169
Net carbon or CO_2 greenhouse emissions [4,5]	-187	-686	-189	-693	-199	-730	-250	-916	-270	-990	-315	-1155
Biofuel share of total biomass	11.4%	11.4%	11.7%	11.6%	16%	16%	22%	22%	31.%	31.%	25.%	25.%
Purchased biofuel share of total biomass	0%		7%		0%		0%		2.80%		2.80%	

[1] Carbon contents: INW=50%; NE-NC softwood = 51%; NE-NC hardwood = 55%; Solid Strip Flooring = 55%; Carbon in logs that was allocated to the product or biofuel. Not all the bark went to biofuels.

[2] Includes purchased wood fuel

[3] Total biofuel burned allocated to final product INW=55kg; NE-NC softwood = 118 kg; NE-NC hardwood = 175 kg; Solid Strip Flooring = 198 kg

[4] Carbon dioxide emissions represent 99% of all carbon containing emissions from the combustion of both fossil and non fossil fuels.

[5] From Table 8a-d. Carbon content of CO_2 = 27.5%. Assumes CO_2 emissions from biofuel equals and offsets carbon sequestered in biofuels.

Table A8a ***Softwood Lumber Emissions - Inland Northwest region*** **cradle-to-gate emissions (kg/m^3) to air allocated to 1 m^3 of product for each life cycle stage.**

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Carbon dioxide, atmospheric sequestration		-726.6600		-726.6600
Carbon dioxide, biogenic	0.0101	116.3222	0.0061	116.3385
Carbon dioxide, fossil	10.8470	93.1009	9.0059	112.9538
Carbon monoxide	0.0000	0.7485	0.0000	0.7485
Sulfur dioxide	0.0062	0.7299	0.0043	0.7404
Nitrogen oxides	0.1956	0.3223	0.0612	0.5790
Methane	0.0142	0.3396	0.0108	0.3646
Carbon monoxide, fossil	0.1058	0.1356	0.0471	0.2885
VOC, volatile organic compounds	0.0053	0.1917	0.0029	0.2000
Particulates, unspecified	0.0011	0.1041	0.0008	0.1060
Methane, fossil	0.0011	0.0463	0.0005	0.0480
Potassium	0.0000	0.0429	0.0000	0.0429
Sulfur oxides	0.0109	0.0144	0.0086	0.0339
Methanol	0.0000	0.0224	0.0000	0.0224
Isoprene	0.0003	0.0189	0.0002	0.0193
NMVOC, non-methane volatile organic compounds	0.0066	0.0066	0.0051	0.0183
Particulates, > 2.5 um, and < 10um	0.0059	0.0084	0.0011	0.0155
Particulates, < 10 um	0.0000	0.0094	0.0000	0.0094
Organic substances, unspecified	0.0000	0.0092	0.0000	0.0092
BTEX (Benzene, Toluene, Ethyl benzene, and Xylene)	0.0000	0.0081	0.0000	0.0082
Hydrogen chloride	0.0001	0.0062	0.0001	0.0063
Acetaldehyde	0.0000	0.0022	0.0000	0.0022
Phenol	0.0000	0.0022	0.0000	0.0022
Formaldehyde	0.0001	0.0011	0.0000	0.0012

120 air emissions reported in LCI, shown here are air emission with greater => 10-3 per cubic meter of product

Table 8b ***Softwood lumber Emissions- Northeast-Northcentral region*** **cradle-to-gate emissions (kg/m^3) to air allocated to 1 m^3 of product for each life cycle stage.**

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Carbon dioxide, atmospheric sequestration		-645.5900		-645.5900
Carbon dioxide, biogenic	0.0103	177.5917	0.0058	177.6077
Carbon dioxide, fossil	14.0140	66.5397	8.4648	89.0185
Carbon monoxide	0.0000	1.1518	0.0000	1.1518
Nitrogen oxides	0.2555	0.3710	0.0575	0.6840
VOC, volatile organic compounds	0.0068	0.6571	0.0028	0.6667
Carbon monoxide, fossil	0.1252	0.1535	0.0443	0.3230
Sulfur dioxide	0.0071	0.2742	0.0040	0.2853
Methane	0.0181	0.1114	0.0102	0.1397
Sulfur oxides	0.0142	0.0435	0.0081	0.0657
Potassium	0.0000	0.0657	0.0000	0.0657
NMVOC, non-methane volatile organic compounds, unspecified origin	0.0085	0.0194	0.0048	0.0327
Particulates, unspecified	0.0013	0.0282	0.0008	0.0302
Isoprene	0.0003	0.0199	0.0001	0.0204
Particulates, < 10 um	0.0000	0.0143	0.0000	0.0143
Particulates, > 2.5 um, and < 10um	0.0079	0.0054	0.0010	0.0143
Organic substances, unspecified	0.0000	0.0140	0.0000	0.0140
Hydrogen chloride	0.0001	0.0100	0.0001	0.0102
Methane, fossil	0.0013	0.0054	0.0005	0.0073
Phenol	0.0000	0.0034	0.0000	0.0034
Sodium	0.0000	0.0015	0.0000	0.0015
Hydrogen fluoride	0.0000	0.0012	0.0000	0.0012

113 air emissions reported in LCI, shown here are air emission with greater => 10^{-3} per cubic meter of product

Table 8c ***Hardwood Lumber Emissions- Northeast-Northcentral region*** **cradle-to-gate emissions (kg/m3) to air allocated to 1 m3 of product for each life cycle stage.**

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included

	Harvesting	Product Manufacturing	Transportation	Total
Carbon dioxide, atmospheric sequestration		-906.4900		-906.4900
Carbon dioxide, biogenic	0.0132	368.7647	0.0095	368.7875
Carbon dioxide, fossil	18.0706	130.7727	14.0365	162.8799
Carbon monoxide	0.0000	2.3829	0.0000	2.3829
Nitrogen oxides	0.3287	0.7988	0.0953	1.2228
VOC, volatile organic compounds	0.0089	1.1936	0.0046	1.2070
Particulates, unspecified	0.0017	1.0519	0.0012	1.0549
Sulfur dioxide	0.0092	0.8018	0.0066	0.8176
Carbon monoxide, fossil	0.1741	0.2528	0.0734	0.5004
Methane	0.0234	0.3072	0.0169	0.3475
Potassium	0.0000	0.1363	0.0000	0.1363
Sulfur oxides	0.0183	0.0545	0.0134	0.0862
Isoprene	0.0003	0.0427	0.0002	0.0433
NMVOC, non-methane volatile organic compounds	0.0110	0.0193	0.0079	0.0382
Methane, fossil	0.0018	0.0282	0.0008	0.0308
Particulates, < 10 um	0.0000	0.0297	0.0000	0.0297
Organic substances, unspecified	0.0000	0.0291	0.0000	0.0291
Particulates, > 2.5 um, and < 10um	0.0100	0.0135	0.0017	0.0252
Hydrogen chloride	0.0002	0.0202	0.0001	0.0204
Phenol	0.0000	0.0070	0.0000	0.0070
BTEX (Benzene, Toluene, Ethyl benzene, and Xylene)	0.0001	0.0043	0.0001	0.0044
Sodium	0.0000	0.0031	0.0000	0.0031
Hydrogen fluoride	0.0000	0.0025	0.0000	0.0025
Manganese	0.0000	0.0016	0.0000	0.0016
Formaldehyde	0.0001	0.0013	0.0000	0.0014
Chlorine	0.0000	0.0014	0.0000	0.0014

114 air emissions reported in LCI, shown here are air emission with greater => 10-3 per cubic meter of product

Table 8c ***Hardwood Flooring Emissions - Northeast-Northcentral region*****. Cradle-to-gate emissions (kg/m3) to air allocated to 1 m3 of product for each life cycle stage**.

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included

	Harvesting	Product Manufacturing	Transportation	Total
Carbon dioxide, atmospheric sequestration		-671.6100		-671.6100
Carbon dioxide, biogenic	0.0139	416.0170	0.0228	416.0537
Carbon dioxide, fossil	19.0109	114.4517	33.5734	167.0359
Carbon monoxide	0.0000	2.6912	0.0000	2.6912
Nitrogen oxides	0.3458	0.7489	0.2280	1.3227
VOC, volatile organic compounds	0.0093	1.2500	0.0110	1.2703
Particulates, unspecified	0.0018	1.0951	0.0030	1.0999
Sulfur dioxide	0.0097	0.7114	0.0159	0.7370
Carbon monoxide, fossil	0.1832	0.2197	0.1756	0.5785
Methane	0.0247	0.2822	0.0403	0.3472
Potassium	0.0000	0.1540	0.0000	0.1540
Sulfur oxides	0.0192	0.0504	0.0320	0.1016
NMVOC, non-methane volatile organic compounds	0.0116	0.0167	0.0190	0.0473
Particulates, < 10 um	0.0000	0.0373	0.0000	0.0373
Isoprene	0.0004	0.0345	0.0006	0.0355
Organic substances	0.0000	0.0329	0.0000	0.0329
Methane, fossil	0.0019	0.0279	0.0020	0.0317
Particulates, > 2.5 um, and < 10um	0.0105	0.0116	0.0041	0.0262
Hydrogen chloride	0.0002	0.0164	0.0003	0.0168
Phenol	0.0000	0.0079	0.0000	0.0079
BTEX (Benzene, Toluene, Ethyl benzene, and Xylene)	0.0001	0.0044	0.0001	0.0046
Sodium	0.0000	0.0036	0.0000	0.0036
Hydrogen fluoride	0.0000	0.0020	0.0000	0.0021
Manganese	0.0000	0.0018	0.0000	0.0018
Chlorine	0.0000	0.0015	0.0000	0.0015
Formaldehyde	0.0001	0.0014	0.0000	0.0015
Dinitrogen monoxide	0.0000	0.0003	0.0008	0.0011

117 air emissions reported in LCI, shown here are air emission with greater => 10-3 per cubic meter of product

Table A8e Cradle-to-gate cumulative emissions summary to air allocated to one cubic meter of *structural wood products* produced in the *Pacific Northwest, Southeast, Inland Northwest (NW) and Northeast-Northcentral (NE-NC)* production regions; includes all life-cycle processes from forest regeneration through wood products production.

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	CORRIM Phase I		CORRIM Phase II			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	Inland NW	NE-NC	NE-NC	NE-NC
	kg/m^3					
CO	1.43	1.83	1.04	1.48	2.88	2.69
CO_2 (biomass)	160.00	248.00	116.34	177.61	368.79	416.05
CO_2 (fossil)	92.00	62.00	112.95	89.02	162.88	167.04
Methane	0.19	0.10	0.37	0.14	0.35	0.35
Nitrogen oxides	0.67	0.64	0.58	0.68	1.22	1.32
NMVOC			0.02	0.03	0.04	0.05
Particulates	0.06	0.09	0.13	0.06	1.11	1.16
Sulfur oxides	1.03	0.43	0.74	0.29	0.82	0.74
Volatile organic compounds	0.08	0.49	0.20	0.67	1.21	1.27
Total	**1.17**	**1.01**	**232.37**	**269.98**	**539.30**	**590.67**

Table A9 Cradle-to-gate emissions (kg/m3) to water allocated to 1 m3 of product for each life cycle stage for softwood lumber manufactured Inland Northwest region.

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Dissolved solids	0.5558	5.0693	0.4296	6.0547
Chloride	0.4507	4.1093	0.3483	4.9083
Sodium, ion	0.1271	1.1589	0.0982	1.3842
Calcium, ion	0.0401	0.3656	0.0310	0.4367
Suspended solids	0.0331	0.0939	0.0256	0.1525
Lithium, ion	0.0007	0.1118	0.0005	0.1129
Magnesium	0.0078	0.0715	0.0061	0.0854
Barium	0.0147	0.0415	0.0114	0.0676
COD, Chemical Oxygen Demand	0.0043	0.0333	0.0033	0.0410
Bromide	0.0027	0.0244	0.0021	0.0291
BOD5, Biological Oxygen Demand	0.0023	0.0199	0.0018	0.0239
Sulfate	0.0010	0.0144	0.0008	0.0162
Iron	0.0021	0.0080	0.0017	0.0118
Strontium	0.0007	0.0062	0.0005	0.0074
Aluminum	0.0011	0.0029	0.0008	0.0048
Oils, unspecified	0.0003	0.0022	0.0002	0.0028
Ammonia	0.0002	0.0015	0.0002	0.0019

101 water emissions reported in LCI, shown here are water emission with greater => 10-3 per cubic meter of product

Table A9 Cradle-to-gate emissions (kg/m3) to water allocated to 1 m3 of product for each life cycle stage for softwood lumber manufactured Northeast-Northcentral.

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Dissolved solids	0.7200	1.7628	0.4038	2.8866
Chloride	0.5838	1.4292	0.3274	2.3403
Sodium, ion	0.1646	0.4030	0.0923	0.6599
Calcium, ion	0.0519	0.1271	0.0291	0.2082
Suspended solids	0.0430	0.0949	0.0241	0.1620
Barium	0.0191	0.0415	0.0107	0.0714
Magnesium	0.0102	0.0249	0.0057	0.0407
COD, Chemical Oxygen Demand	0.0056	0.0134	0.0031	0.0222
Sulfate	0.0013	0.0129	0.0007	0.0149
Bromide	0.0035	0.0085	0.0019	0.0139
BOD5, Biological Oxygen Demand	0.0030	0.0072	0.0017	0.0118
Iron	0.0028	0.0066	0.0016	0.0109
Lithium, ion	0.0008	0.0081	0.0005	0.0094
Aluminum	0.0014	0.0032	0.0008	0.0054
Strontium	0.0009	0.0022	0.0005	0.0035
Oils, unspecified	0.0004	0.0009	0.0002	0.0015
Ammonia	0.0003	0.0007	0.0002	0.0012

99 water emissions reported in LCI, shown here are water emission with greater => 10-3 per cubic meter of product

Table A9c. Cradle-to-gate emissions (kg/m3) to water allocated to 1 m3 of product for each life cycle stage for hardwood lumber manufactured Northeast-Northcentral.

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Dissolved solids	0.9301	3.7216	0.6696	5.3213
Chloride	0.7541	3.0170	0.5429	4.3140
Sodium, ion	0.2126	0.8508	0.1531	1.2165
Calcium, ion	0.0671	0.2684	0.0483	0.3838
Suspended solids	0.0555	0.1171	0.0399	0.2125
Barium	0.0247	0.0505	0.0178	0.0930
Magnesium	0.0131	0.0525	0.0094	0.0750
Lithium, ion	0.0011	0.0592	0.0008	0.0611
COD, Chemical Oxygen Demand	0.0073	0.0258	0.0052	0.0383
Sulfate	0.0017	0.0276	0.0012	0.0305
Bromide	0.0045	0.0179	0.0032	0.0256
BOD5, Biological Oxygen Demand	0.0038	0.0148	0.0027	0.0214
Iron	0.0036	0.0091	0.0026	0.0153
Aluminum	0.0018	0.0039	0.0013	0.0071
Strontium	0.0011	0.0046	0.0008	0.0065
Oils, unspecified	0.0005	0.0018	0.0003	0.0026
Ammonia	0.0004	0.0012	0.0003	0.0019

100 water emissions reported in LCI, shown here are water emission with greater => 10-3 per cubic meter of product

Table A9d. Cradle-to-gate emissions (kg/m3) to water allocated to 1 m3 of product for each life cycle stage for *hardwood flooring* manufactured *Northeast-Northcentral.*

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	Harvesting	Product Manufacturing	Transportation	Total
Dissolved solids	0.9785	3.6093	1.6015	6.1893
Chloride	0.7934	2.9259	1.2984	5.0178
Sodium, ion	0.2237	0.8252	0.3661	1.4150
Calcium, ion	0.0706	0.2603	0.1155	0.4464
Suspended solids	0.0584	0.1076	0.0955	0.2616
Barium	0.0260	0.0467	0.0426	0.1152
Magnesium	0.0138	0.0509	0.0226	0.0873
Lithium, ion	0.0011	0.0601	0.0018	0.0631
COD, Chemical Oxygen Demand	0.0076	0.0249	0.0125	0.0450
Bromide	0.0047	0.0174	0.0077	0.0298
Sulfate	0.0018	0.0233	0.0029	0.0280
BOD5, Biological Oxygen Demand	0.0040	0.0143	0.0066	0.0249
Iron	0.0038	0.0084	0.0062	0.0184
Aluminum	0.0019	0.0036	0.0031	0.0086
Strontium	0.0012	0.0044	0.0020	0.0076
Water	0.0000	0.0062	0.0000	0.0062
Oils, unspecified	0.0005	0.0017	0.0008	0.0031
Ammonia	0.0004	0.0012	0.0007	0.0023

110 water emissions reported in LCI, shown here are water emission with greater => 10-3 per cubic meter of product

Table A9e Cradle-to-gate cumulative emissions summary to air allocated to one cubic meter of *structural wood products produced* in the *Pacific Northwest, Southeast, Inland Northwest (NW) and Northeast-Northcentral (NE-NC)* production regions; includes all life-cycle processes from forest regeneration through wood products production. (Updated from publication 1)

Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.

	CORRIM Phase I		CORRIM Phase II[1]			
	Softwood lumber		Softwood lumber		Hardwood lumber	Hardwood flooring
	PNW	SE	Inland NW	NE-NC	NE-NC	NE-NC
	kg/m^3					
BOD5, Biological Oxygen	0.0015	0.0004	0.239	0.0118	0.0214	0.0249
Chloride	0.0643	0.0131	4.908	2.3403	4.3140	5.0179
COD, Chemical Oxygen	0.0203	0.0042	0.0410	0.0222	0.0383	0.0450
Dissolved solids	1.4205	0.2914	6.0547	2.8866	5.3213	6.1893
Oils, unspecified	0.0251	0.0053	0.0028	0.0015	0.0026	0.0031
Suspended solids	0.0306	0.0254	0.1525	0.1620	0.2125	0.2616
Total	1.5622	0.3397	11.398	5.4244	9.9101	11.5418

[1] Differences due to electricity generation. CORRIM reports provided electricity fuel sources based on region from which the surveys were performed based on EIA state electricity generation reports http://www.eia.doe.gov/cneaf/electricity/epav1/epav1_sum.html). While the US LCI databases utilizes Reliable Council electricity grids (www.nrel.uslci.gov).