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Life-Cycle Assessment of Redwood Decking in the United States with a Comparison to Three Other Decking Materials

Final Report

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July 31, 2013

Executive Summary

Study Goals

The goal of the study was to conduct a life-cycle inventory (LCI) of California redwood (*Sequoia sempervirens*) decking that would quantify the critical environmental impacts of decking from cradle to grave. Using that LCI data, a life-cycle assessment (LCA) was produced for redwood decking. The results were used to compare the environmental footprint of redwood decking to other decking materials that serve an equivalent function. The other materials examined include plastic (cellular PVC) and wood–plastic composites (WPCs) with recycled content varying from 0% and 100%.

Methodology

The environmental impacts were determined using LCA techniques conducted to ISO 14040 and 14044 standards. System boundaries delineated the life cycle covered from extraction through product production and maintenance to disposal of old decking into a landfill with standard methane capture equipment for energy recovery. The present study chose the functional unit as 100 square feet (9.29 m^2) of installed decking in service for 25 years. Twenty-five years is the expected service life of all decking materials. TRACI 2.1 method found in SimaPro 7 modeled the life-cycle impact assessment (LCIA) per functional unit. Softwood shavings used in making WPC decking products left the sawmill with no environmental burdens assigned to them. The biogenic methane captured from the landfill avoided natural gas production.

Impact Measures

Impact categories include global warming potential (GWP) (kg CO_2-eq), acidification potential (kg SO_2-eq), respiratory effects (PM 2.5-eq), eutrophication potential (kg N-eq), ozone depletion (kg CFC-11-eq), and smog potential (kg O_3-eq). Other impact measures included cumulative (total) energy demand (primary energy) (MJ-eq), including both the biomass and fossil fuel contributions, were calculated and reported directly from LCI flows. The present study also tracked fresh water consumption (in L) and renewable and non-renewable material resource consumption (non-fuel resources). Impact categories and other impact measures were reported per 100 ft^2 (9.29 m^2) and per m^3. Carbon stored in the decking was accounted for in GWP.

Key Findings

The following table shows the LCIA per functional unit for PVC (156 kg), virgin WPC (266 kg), recycled WPC (266 kg) and redwood (135 oven-dried kg). PVC and both WPC decking products assumed a 2.3% loss, whereas redwood decking assumed a 3% loss over their whole life cycle. For two reasons, global warming potential (GWP) for redwood (–163 kg CO_2-eq) was negative. One, the carbon sequestered in the trees that are used as raw material for the redwood decking, continued to be stored in the decking while in use (–262 kg CO_2-eq). Secondly, redwood decking consumed little energy for drying, which is usually the most energy-intensive process for wood products. Even though the two WPC decking materials stored carbon as a final product (50% by weight) as well, all six key impact categories were still substantially higher in value for the alternative decking materials than for redwood decking. Biomass energy consumption was higher for redwood decking than for the alternatives, as expected, because wood product production typically utilizes the wood residue generated during production as a fuel source. However, total energy for redwood was substantially lower than the other decking products: 4.2% (447/10640) of PVC, 3.0% (447/14700) of virgin WPC and 6.7% (447/6690) of recycled

WPC. The volume of captured biogenic methane from decomposing redwood decking in landfills to avoid natural gas production was 11.3 m^3/100 ft^2, approximately 433 MJ/100 ft^2 of energy.

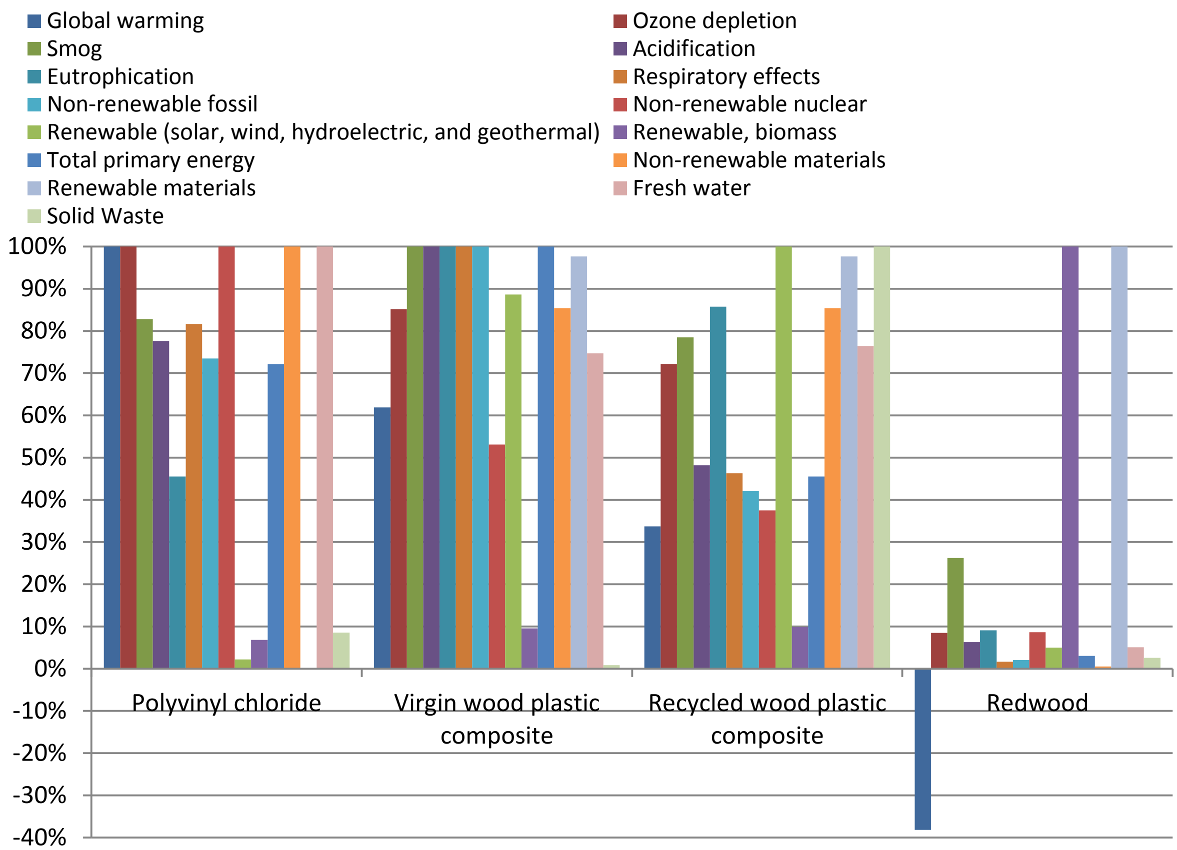
Life-cycle impact assessment for four decking products by value per 100 ft^2 (9.29 m^2)

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	426	264	144	–163
Ozone depletion	kg CFC-11 eq	1.60E-05	1.37E-05	1.16E-05	1.36E-06
Smog	kg O_3 eq	30.0	36.3	28.5	9.5
Acidification	kg SO_2 eq	4.61	5.94	2.86	0.21
Eutrophication	kg N eq	0.108	0.237	0.203	0.022
Respiratory effects	kg PM2.5 eq	0.276	0.338	0.157	0.006
Primary energy consumption	Unit				
Non-renewable fossil	MJ	10169	13840	5820	280
Non-renewable nuclear	MJ	449	238	168	39
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	614	693	35
Renewable, biomass	MJ	6	9	9	94
Total primary energy	MJ	10600	14700	6690	447
Material resources consumption[1]	Unit				
Non-renewable materials	kg	157	134	134	0.8
Renewable materials	kg	0	133	133	136
Fresh water	L	4500	3360	3440	229
Waste generated	Unit				
Solid waste	kg	0.736	0.070	8.60	0.223

[1] Non-fuel resources.

Kiln-drying is the most energy-intensive activity for making most wood products. However, in this respect, redwood decking is different because of the amount that sold green or first air-dried before being kiln-dried. Approximately 36% of redwood decking was sold green, with the remaining 64% being air-dried. After air-drying to less than 30% moisture content, 57% of the decking is further dried in the kiln so that 36.6% of total redwood decking leaves the mill as a kiln-dried product. Therefore, minimal kiln-drying resulted in a redwood decking product comparable on an energy-consumption basis to structural Douglas-fir (*Pseudotsuga menziesii*) that is sold and installed green.

The following figure illustrates the relative differences between the critical environmental impacts associated with the four decking materials per functional unit.



Life-cycle impact assessment for the four decking products by percentage per 100 ft^2 (9.29 m^2)

Interpretation

Redwood decking had considerably lower values for the six key impact categories, compared to the other three decking materials. The low GWP ranking for redwood decking was the result of the product's ability to store carbon, originally sequestered from the atmosphere, over the life of the product. The LCIA incorporated carbon stored in all decking products through sequestration including WPC decking. Biogenic carbon dioxide emissions were not considered but biogenic methane emissions were in the LCIA to be consistent with the TRACI method. Additionally, the present study considered that 96% of the carbon in the wood residues generated during decking production was emitted to the atmosphere as biogenic carbon dioxide. Whereas the remainder (4%) was stored in a new product separate from redwood decking.

As indicated by the six impact categories, producing recycled WPC had substantial environmental advantages over using virgin WPC. All six key impact categories were lower for recycled WPC than for virgin WPC. The negative environmental impact for recycled WPC compared to virgin WPC was solid waste generated during the cradle-to-gate production of recycled WPC.

The other impact measures indicated the high consumption of both non-renewable and renewable material resources in the virgin and recycled WPC decking products. WPC decking products are made of 50% polyethylene resins and 50% wood. In addition, WPC decking products are substantially denser than the other decking products; therefore, the two WPC decking products consume roughly the same as PVC in the non-renewable resource category and redwood decking in the renewable resource category.

Sensitivity Analysis

The present study conducted a sensitivity analysis to determine the environmental impacts assigned to the final product. For the base case, the present study allocated no environmental impacts to the co-products or by-products. Instead, all burdens were assigned to the final product (no allocation). To evaluate the decision, a sensitivity analysis was conducted assuming mass allocation. Redwood decking was the only decking product that had other co-products associated with its production such as green and dry wood residues.

All six impacts for redwood decking were lower for the mass allocation than the base case. The impacts for the other three decking materials stayed the same. Because of mass allocation, GWP for redwood decking was slightly more negative (–175 kg CO_2-eq) compared to no allocation conducted (–163 kg CO_2-eq). GWP for redwood decking was lower for the mass allocation scenario primarily because the green wood residues were allocated a portion, about 40% of the environmental impacts originally assigned to the redwood decking in the base case scenario. The following table shows the LCIA per functional unit for mass allocation.

Life-cycle impact assessment for four decking products per 100 ft^2 (9.29 m^2) (Mass allocation)

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	426	264	144	–175
Ozone depletion	kg CFC-11 eq	1.60E-05	1.37E-05	1.16E-05	1.25E-06
Smog	kg O_3 eq	30.0	36.3	28.5	6.7
Acidification	kg SO_2 eq	4.61	5.94	2.86	0.09
Eutrophication	kg N eq	0.108	0.237	0.203	0.016
Respiratory effects	kg PM2.5 eq	0.276	0.338	0.157	0.001
Primary energy consumption	Unit				
Non-renewable fossil	MJ	10169	13836	5823	95
Non-renewable nuclear	MJ	449	238	168	27
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	614	693	24
Renewable, biomass	MJ	6	9	9	86
Total primary energy	MJ	10600	14700	6690	232
Material resources consumption[1]	Unit				
Non-renewable materials	kg	157	134	134	1
Renewable materials	kg	0	133	133	138
Fresh water	L	4500	3350	3430	189
Waste generated	Unit				
Solid waste	kg	0.736	0.070	8.60	0.220

[1] Non-fuel resources.

Recommendations

As shown by its negative GWP, the amount of carbon stored in redwood decking exceeded the total GHG emissions emitted during its whole life cycle. Other wood building products and wood composites have this significant environmental advantage of storing carbon while in use to offset the impacts from production. The uptake of carbon dioxide from the atmosphere into the raw materials (i.e., trees) used to make wood products and the storage of the resultant carbon in a long-lived product is a significant environmental benefit.

The substantially lower rankings across all six critical impact categories for redwood decking quantify its lower environmental footprint relative to alternative decking materials. Other life-cycle studies have shown similar results for wood products.

Acknowledgments

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1 Introduction

The main scope of this project was to identify the critical environmental impacts of using redwood as a decking material relative to competing materials, including polyvinyl chloride (PVC) and wood–plastic composites (WPCs) at various recycled content (0% and 100%) for residential use. The environmental impact was determined using life-cycle assessment (LCA) techniques conducted to ISO 14040 standards. Conducting the LCA to these standards provided the added credibility that the results were not only scientifically sound, but were reviewed by independent experts. Additionally, the present study provided underlying LCA data should the California Redwood Association (CRA) choose to pursue environmental product declarations (EPD).

1.1 Background

The Consortium for Research on Renewable Industrial Materials (CORRIM) is a non-profit research consortium with members from 16 universities and research institutions. Using a scientifically rigorous methodology, CORRIM has set out to evaluate the environmental performance of wood by researching the impacts of wood materials using the standardized tools of life-cycle analysis. CORRIM has helped build a multi-national database of the environmental and economic impacts associated with using renewable materials (Bowyer *et al.* 2001). CORRIM has provided wood building material's LCI data to the United States Life Cycle Inventory (US LCI) Database (USDA 2013). The present decking LCA study used the methodology and protocols put forth by CORRIM and ISO standards (CORRIM 2010; ISO 2006a; 2006b).

LCI data are a major component of a LCA. LCA uses rigorous methodology to find the critical environmental impact for a particular product, referred to as "cradle-to-grave" (raw material extraction to waste disposal) analysis. LCI measures all the raw material and energy inputs and outputs required to manufacture a particular product on a per unit basis within carefully defined system boundaries. The current LCI study includes forest resources, resource transportation, manufacturing, product transportation, final product use, maintenance, and final disposal for redwood decking (**Figure 1-1**) (ISO 2006a; 2006b).

In the present study, forest resources include stand establishment and raw material extraction. Stand establishment involves nursery operations, seedling planting activities, intermediate treatment activities (fertilization and pre-commercial thinning/selection), and silvicultural systems used. The analysis includes the environmental and energy costs on a per unit basis using data from individual LCI studies.

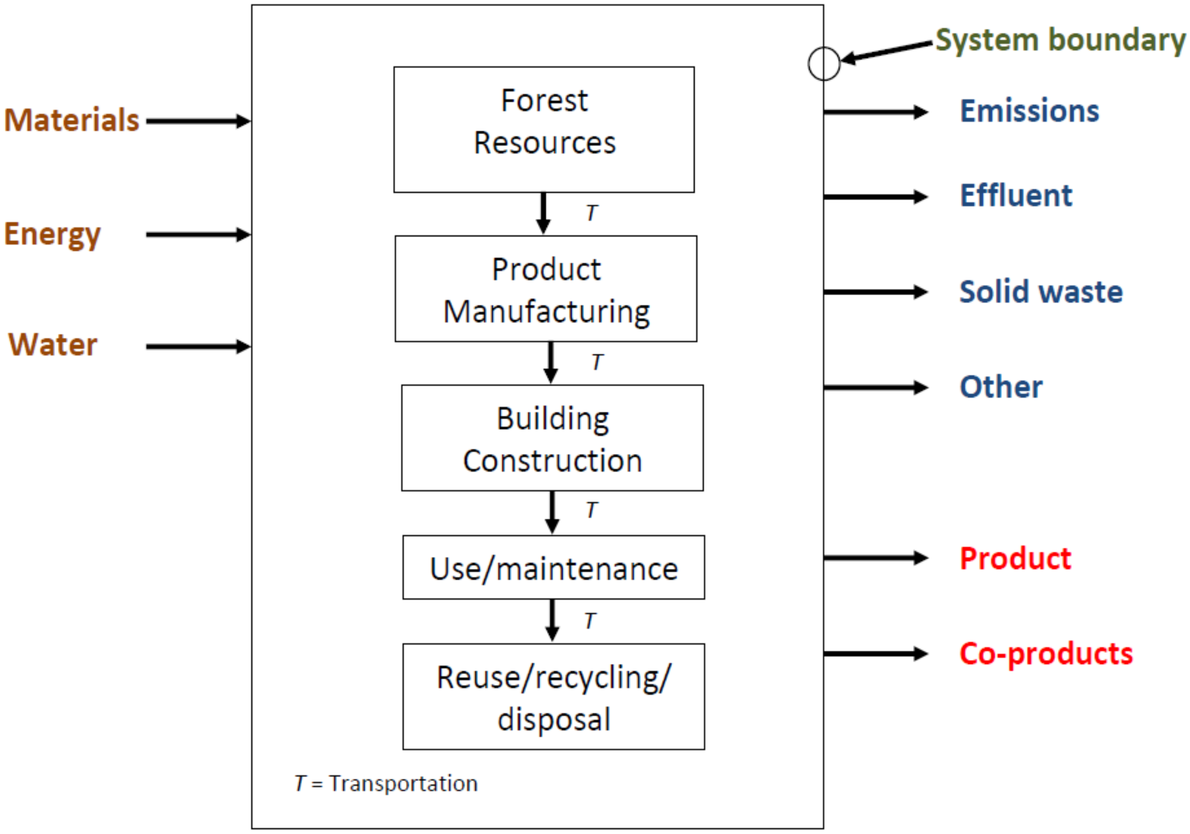

Figure 1-1: Complete life cycle from regeneration of trees to disposal of wood materials (Based on Fava et al. 1994).

A LCA is comprised of four stages (phases) as defined by the ISO. These are 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation (**Figure 1-2**). A LCA study includes all stages, but a LCI study does not include stage 3, the impact assessment (SAIC 2006, ISO 2006a; ISO 2006b).

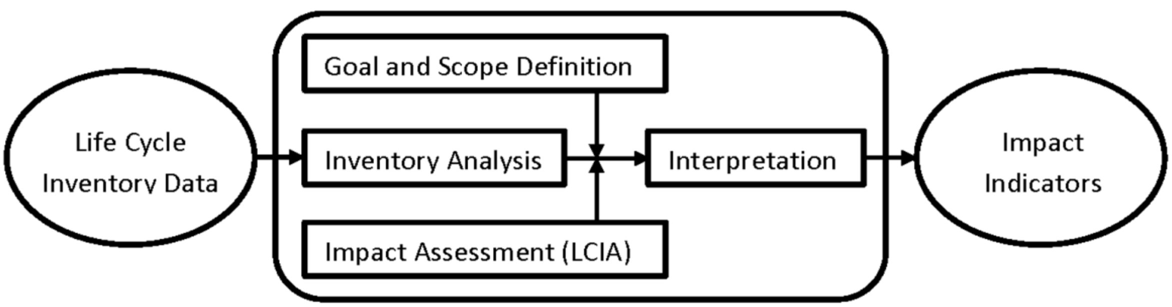

Figure 1-2: Life-cycle assessment phases.

The full life-cycle study can provide information about the potential environmental impacts associated with a product or service or the impacts implied by any product selection decision. It represents the holistic yardstick of environmental performance. That assists us to understand and avoid possible "burden shifting;" such as from the manufacturing to the use phase of the product's life cycle, or resolving environmental problems while simultaneously creating economic or social problems.

1.2 Significance

A redwood decking LCA can be important to both manufacturing and consumer groups. This LCA information could be useful to wood product manufacturers, policy makers, and consumers concerned with the physical environment, the sustainability of natural resources, and sustainability of local businesses.

Consumers make choices to buy or use products made from metal, wood, plastic, or concrete daily. Consumers base product selection on a broad range of attributes including price, quality, and intended service application. In recent decades, the burdens that a particular product may place on human health and the physical environment have begun receiving increased consideration. To help make informed product choices consumers need transparent, scientifically verified, unbiased life-cycle information.

The LCA methodology used by CORRIM can provide this information as it has for an array of wood products across multiple geographic regions using LCIs. However, no such inventory or LCA was completed for redwood decking in the United States. Given the popularity of redwood for residential decking, an evaluation of the collective material and energy inputs and outputs required to manufacture this product was needed.

2 Goal of the study

The goal of the study was to identify the critical environmental impacts of using redwood as a decking material relative to plastic (cellular PVC) and WPCs at various recycled content (0% and 100%) for residential use. From this point on, cellular PVC is referred to as PVC in this paper. The environmental impact was determined using LCA techniques conducted to ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards. Conducting the LCA to these standards provided the added credibility that the results were not only scientifically sound, but they had been third-party reviewed by a panel of independent experts. This extra level of effort was aimed at performing a comparative assertion between the four decking materials. The LCA outcomes resulted from this study were intended to be used in a comparison for future disclosure to the public. In addition, a third-party review supported future endeavors should the CRA and its members, the primary intended audience, choose to pursue environmental product declarations (EPDs), a Type III eco-label for redwood decking.

Other intended audiences included manufacturers and policymakers as well as buyers of decking material. For decking manufacturers, the continuous improvement of the manufacturing process is essential to remaining competitive. Through the collection of primary forestry and manufacturing data required to model the LCA of redwood decking, the present study identified improvement opportunities for participating redwood sawmills in the areas of wood use, efficiency, and energy efficiency. A full-length comprehensive report will be made available on the CORRIM website (www.corrim.org). ***Only data in an aggregated form will be released publicly to protect proprietary information.***

3 Methodology

3.1 Scope of the Study

The scope of the study covered the full life cycle of redwood decking and decking made from PVC and WPC at 0% and 100% recycled content. **Figure 3-1** shows the region of northern California where both harvesting of redwood decking logs and the conversion of logs into the final product occurred. Redwood decking production is primarily a local activity: forest management practices and product manufacturing processes take place along coastal northern California. The dimensions for redwood decking examined were 38 × 140 mm (2 × 6 in). The redwood decking LCA was constructed using primary data to evaluate the environmental impacts of redwood decking. WPC and PVC decking LCAs were constructed from peer-reviewed literature and other secondary and tertiary data sources. Redwood, PVC, and WPC decking materials were evaluated on a functionally equivalent basis with respect to service life. The service life selected for those four decking materials was 25 years. Results included cumulative energy consumption, air emissions, fresh water usage, material resource consumption, and solid waste.

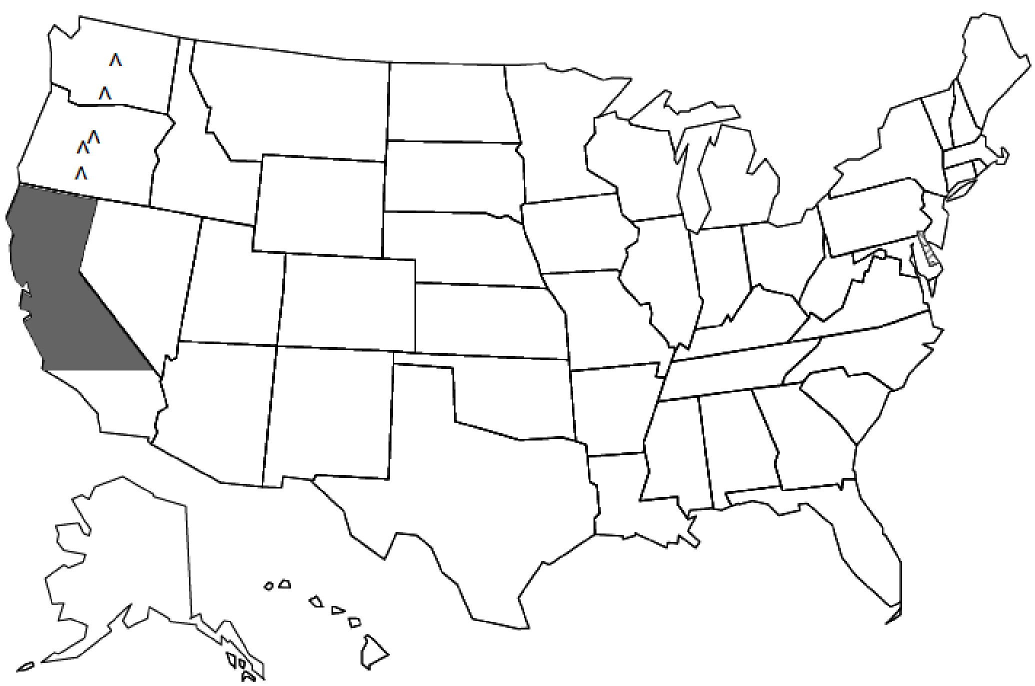

Figure 3-1: Shaded region shows area of redwood decking production.

3.2 Functional Unit

Delineating system boundaries determined the unit processes to include in the analysis and standardized material flows, energy use, and emission data. The functional unit of installed 100 ft^2 (9.29 m^2) of decking material was selected with a service life of 25 years, and the thickness depending on material selection. The other three decking materials were assumed to have a service life of 25 years as well. The U.S. decking industry uses square footage. Therefore, the unit of 100 ft^2 was preferred over SI unit of square meters, which is typical for markets outside the United States. Based on U.S. industry measures, we used the conversion of 1,000 board feet (MBF) of green and dry wood decking equally 2.36 m^3 and 1.62 m^3, respectively, because wood shrinks as it dries from its green state to its final dry state and is planed (Bergman 2010). For dry redwood decking, 10 m^2 at 38-mm thickness equals 0.375 m^3 (231 bf). Decking is usually sold by the board. A one 8-ft 2 × 6-in green and dry wood board is considered 8 bf (i.e., 1 bf per linear foot) whether green or dry. Results of the LCIA and other impact measures were reported on a 100 ft^2 (9.29 m^2) and m^3 basis.

Table 3-1 shows reference flows and actual thicknesses for the following decking products: redwood, WPC, and PVC.

Table 3-1: Reference flows for redwood, polyvinyl, and wood–plastic composite decking

Decking material	Mass (kg/m^3)	Reference flow ($kg/10m^2$)	Reference flow ($kg/100ft^2$)	Reference flow (kg/1000 bf)	Thickness (mm)	Conversion (100 ft^2/m^3)
Redwood[1]	380	145	135	897	38	0.354
Polyvinyl chloride	660	168	156	1,557	25	0.236
Virgin WPC[2]	960	287	266	2,265	25	0.277
Recycled WPC[2]	960	287	266	2,265	25	0.277

[1] Miles and Smith 2009 (properties measured at 12% MC and mass values listed as oven-dry).
[2] Klyosov 2007.

3.3 System Boundary

This project considered the full life cycle of all the decking products, starting from raw material extraction to final disposal in a municipal solid waste (MSW) landfill with methane capture (**Figure 3-2**). For redwood decking, raw material extraction included forest resources. Forest resources included stand establishment and activities such as nurseries. Additionally, do-it-yourselfers complete most decking projects and usually send their old decking material, when replaced, to a MSW landfill. California, the largest market for redwood decking, has passed regulations in 2011 requiring landfills without equipment to install methane capture technology by 2012[1]. An additional scenario analysis was conducted on the end-of-life approach from the Mahalle and O’Connor (2009) study indicating that only 59% of MSW landfills had landfill gas collection systems (EPA 2006; Themelis and Ulloa 2007). Joists and posts used to support the deck were omitted from this analysis since these materials are common for all systems.

[1] http://www.calrecycle.ca.gov/LEA/Mail/2009/MethaneCap.htm.

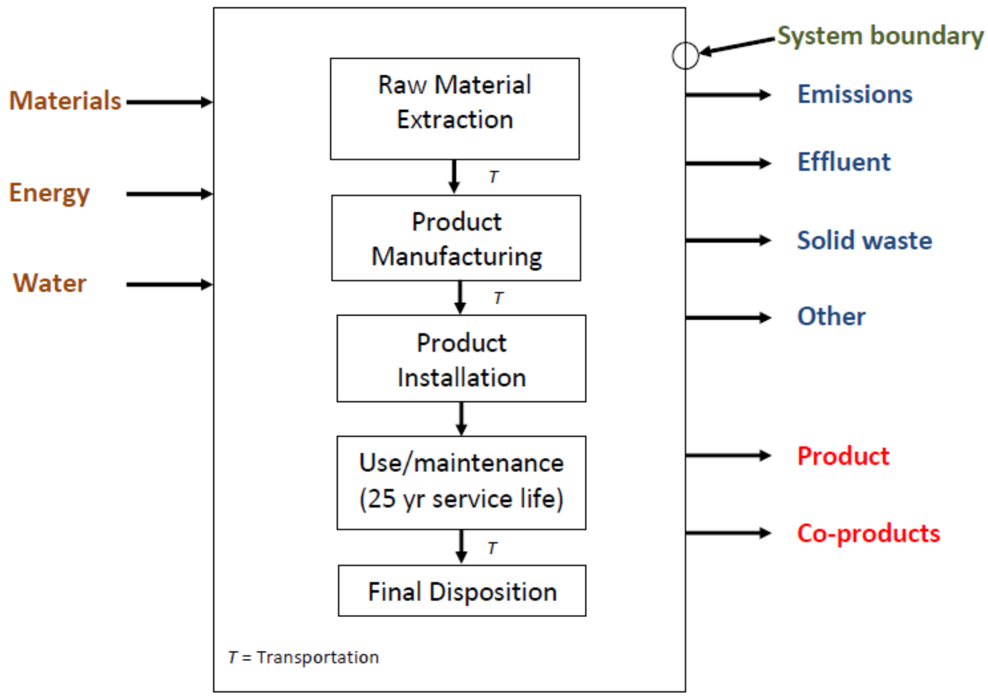

Figure 3-2: System boundary for decking from cradle-to-grave.

3.4 Allocation Procedures

Defining the allocation between co-products for LCI flows of emission data and energy and material inputs is a necessary step of the LCA process. In the present study, WPC and PVC decking did not require an allocation method because their manufacturing did not generate any co-products that were not reground and mixed back into the final product. Therefore, all emissions and inputs were attributed solely to the decking product. In contrast, redwood decking required the selection of an allocation method because there were a number of co-products produced along with the decking lumber.

For redwood, mills produce many other redwood lumber products in addition to the 38- × 140-mm decking (**Figures 3-3**). Additionally, redwood mills process some Douglas-fir (*Pseudotsuga menziesii*) logs into rough green lumber. Therefore, the 38- × 140-mm (nominal 2- × 6-) redwood decking must be separated from Douglas-fir products and then further allocated redwood logs on a mass basis between the various redwood products based on the weighted average input for the redwood sawmills surveyed.

As redwood decking products are far more expensive (10:1 ratio) than the wood residues produced during the manufacturing process (such as bark, sawdust, and chips), all LCI burdens were assigned to the redwood decking just like the other decking products. Thus, in the case of redwood decking products, no LCI burdens were assigned to the wood residues. The wood residues were still considered during the calculation of the wood mass balance. Therefore, the present study allocated all LCI flows to the redwood decking and none to the wood residue generated during the production of the redwood decking. A sensitivity analysis was conducted on a mass allocation approach for comparison.

In practice, this resulted in the burdens from the redwood wood residues, which represented about 40% of the mass of the logs entering the sawmill, being allocated to the redwood products on a mass basis. As an example, if the condition arises that 30% of the incoming redwood log mass becomes redwood decking, and another 30% becomes other redwood lumber products, the remaining 40% of the incoming redwood logs are various wood residues[2]. In this case, since no LCI burdens are assigned to the wood residues, 50% of the LCI burdens are assigned to the redwood decking (30% from decking plus half the residue burden or 20%) and 50% to the other redwood lumber products because the mass of the two categories of redwood products (redwood decking and other redwood lumber products) are equal.

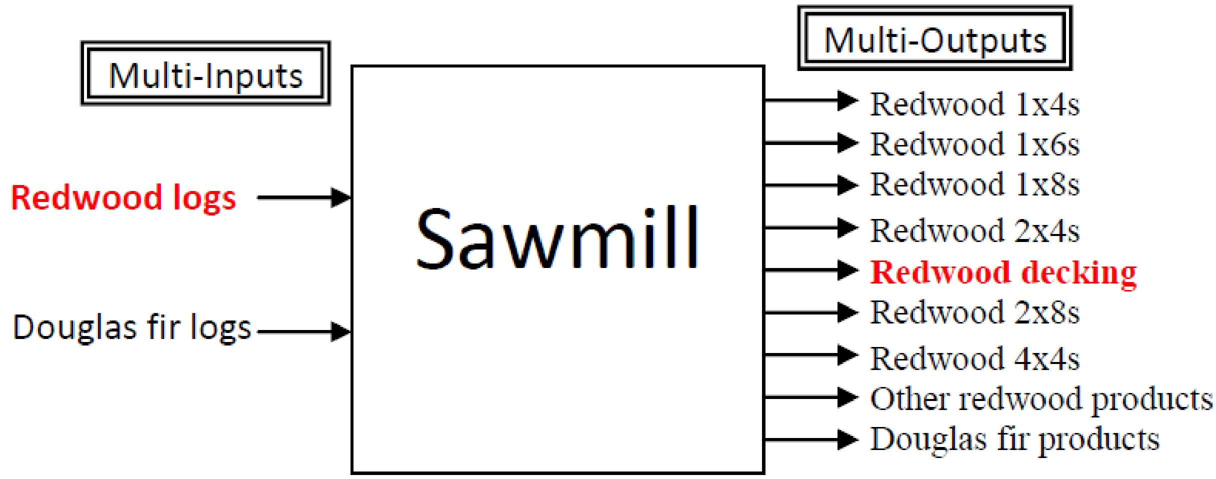

Figure 3-3: Diagram showing the wood flow through the production center (i.e., sawmill).

3.5 Decking

3.5.1 *Plastic (PVC)*

Plastic decking, which is primarily made from PVC, has a relatively small market share but it has the fastest market growth. Plastic decking currently sold in the California market is referred to as cellular (solid) PVC. Unlike cellular PVC decking, hollow PVC products have been unable to pass the California State Fire Marshals Code for Wildland Urban Interface Zones and are of no interest in this study[3]. Cellular PVC is about half the weight of standard PVC because of a foaming agent added during the manufacturing process, which is referred to as acrylic foam cell stabilizer (Anonymous 2009). For this report and previously mentioned, the term "PVC decking" was used to refer to cellular PVC unless otherwise specifically noted. The primary component used to manufacture about 85% of PVC decking is PVC resin. PVC resin is made from an ethylene dichloride-vinyl chloride monomer through polymerization. The monomer is produced from chlorine and ethylene derived from natural gas with the addition of liquid oxygen. **Figure 3-4** shows the manufacturing process diagram of plastic decking starting with PVC resin and the addition of the foaming agent (FAL 2010; PRé Consultants 2013; Trex 2009; Lippiatt 2007).

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[2] The ratio of 60% products and 40% wood reside is maintained regardless of the redwood product produced.
[3] Personal communication 10/25/2011 Charlie Jourdain, California Redwood Association.

The US Ecoinvent (EI) database provided an extrusion process for plastics based on European manufacturing data. This study modified data by considering energy consumption from U.S. energy sources. This was the best data source available in the SimaPro model to make meaningful comparisons. Inherent in this data choice, region-specific data on energy sources were incorporated into the plastic manufacturing databases.

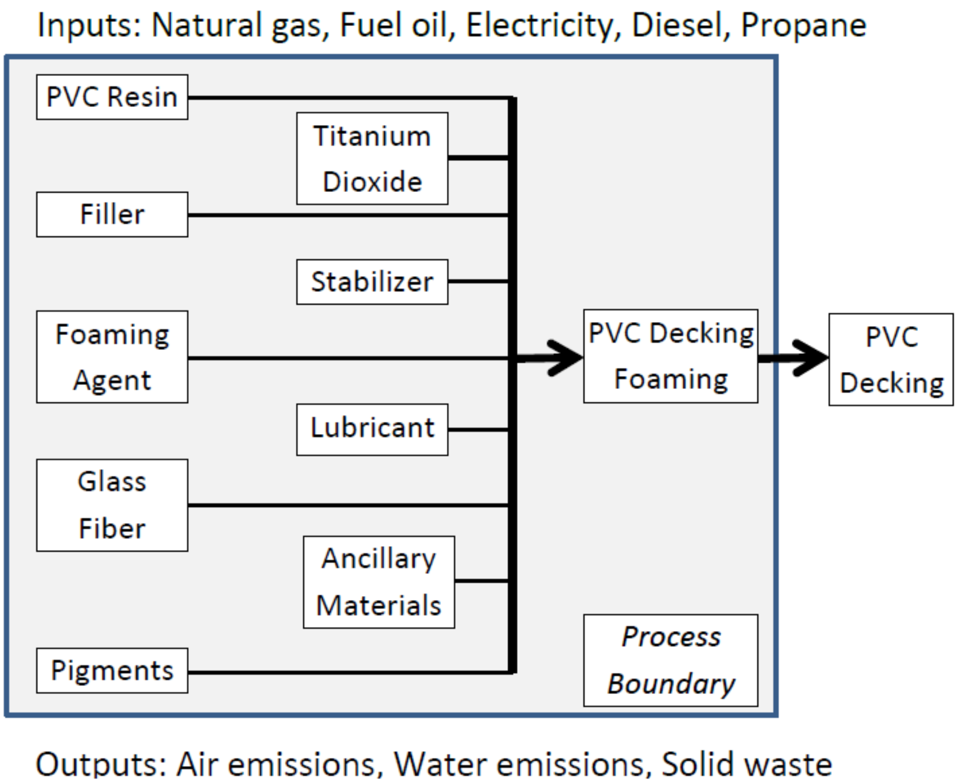

Figure 3-4: Cradle-to-gate manufacturing process diagram for cellular PVC decking (Mahalle and O'Connor 2009).

3.5.2 *Wood–plastic Composites (WPC)*

WPC decking has a larger market share than PVC decking but its share is still less than wood decking. WPC decking is manufactured using a mixture of wood fiber and plastic resins plus some ancillary materials. WPC uses polyethylene (PE) as its primary feedstock. Two of the most common resins used in WPC are high-density polyethylene (HDPE) and low-density polyethylene (LDPE) (FAL 2010; Klyosov 2007).

The focus of the present study was on both virgin and recycled PE used to manufacture WPC decking. Mahalle and O'Connor (2009) provide the basis for the WPC decking formulations used in this study. **Figures 3-5** and **3-6** illustrate the cradle-to-gate manufacturing process for virgin and recycled WPC decking, respectively. The source material used to manufacture recycled WPC is generally derived from plastic grocery and retail bags. Other sources include #2 recycled products such as detergent and soft drink bottles. However, clean plastic bags used in the present study are the preferred feedstock in the recycling process to eliminate additional processing steps, such as washing and drying (Climenhage 2003).

Hammermills grind dry wood shavings into wood flour. Blenders combine the wood flour with PE resin and other materials during the WPC extrusion process. WPC decking is primarily made on the East Coast but there is one manufacturing plant located in Fernley, NV, that supplies the West Coast (http://www.wpcinfo.org/producers/deck/). Details from this plant were used in our model to most fairly represent the comparisons between redwood decking and competing products.

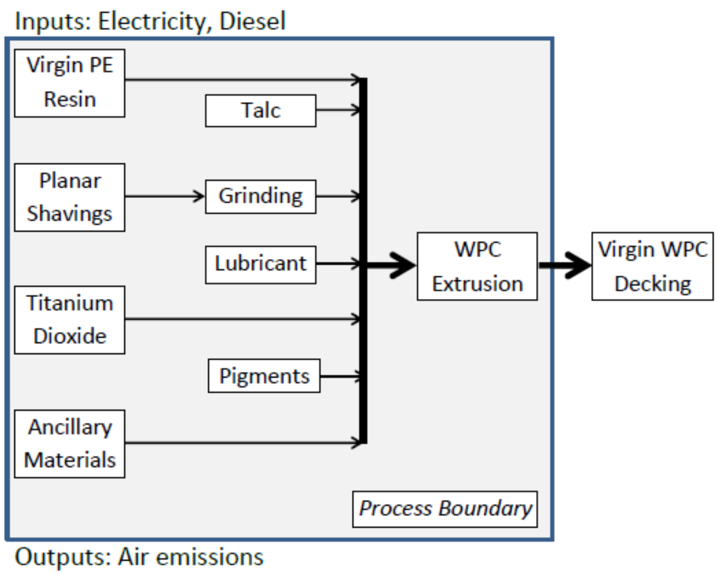

Figure 3-5: Cradle-to-gate manufacturing process diagram for virgin WPC decking (Mahalle and O'Connor 2009).

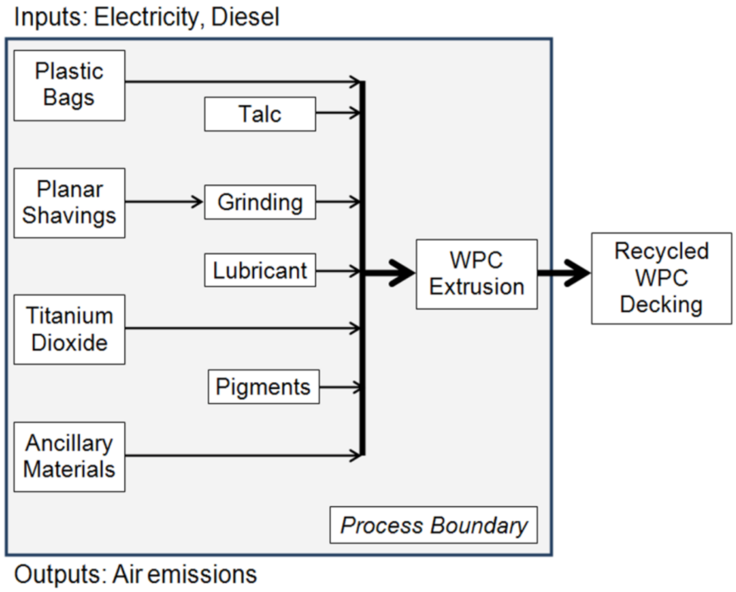

Figure 3-6: Cradle-to-gate manufacturing process diagram for recycled WPC decking (Mahalle and O'Connor 2009).

The US EI database included an extrusion process for plastics that provides energy consumption. The extrusion process included all available US LCI Database data in the SimaPro model.

3.5.3 *Redwood*

Redwood logs are sawn into decking with some wood residues generated. Green wood residues include sawdust, chips, hog fuel, and bark. Planing rough lumber generates shavings. Some redwood decking is kiln-dried after being air-dried. Approximately 36% of redwood decking was sold green, with the remaining 64% being air-dried. After air-drying to less than 30% MC, 57% of the decking is further dried in the kiln so that 36.6% of total redwood decking leaves the mill as a kiln-dried product. Redwood decking is primarily sold on the West Coast with only a small volume of material being shipped east. **Figure 3-7** describes the basic unit processes and the system boundaries for cradle-to-gate manufacturing of redwood decking. Inputs include packaging as well as electricity, diesel, natural gas, steam, propane, and gasoline.

Redwood decking is processed similarly to other types of lumber products. A comparable wood product to redwood decking is structural Douglas-fir lumber. It was cited in a LCI study done by Milota in 2004 because most Douglas-fir is sold and installed green. In addition, since most redwood decking is not kiln-dried or at least not kiln-dried until first air-dried; manufacturing redwood wood decking uses significantly less energy than that of other wood materials (Puettmann et al. 2010). CORRIM has previously studied involving certain grades of Douglas-fir structural lumber that are not kiln-dried (Milota et al. 2004; Puettmann and Wilson 2005).

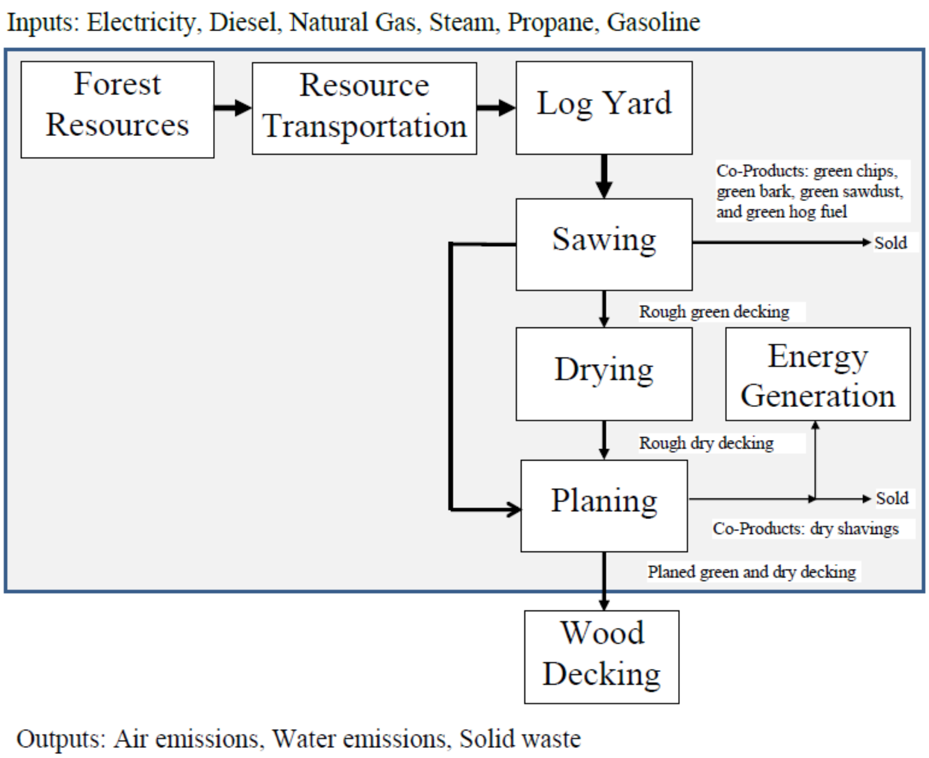

Figure 3-7: Cradle-to-gate wood decking manufacturing (Puettmann et al. 2010).

3.6 Life-Cycle Impact Assessment Methodology and Types of Impacts

Once the complete cradle-to-grave LCI has been constructed for redwood decking, the following environmental mid-point impact categories of global warming potential (kg CO2-eq), acidification potential (kg SO_2-eq), respiratory effects (PM 2.5-eq), eutrophication potential (kg N-eq), ozone depletion (kg CFC-11-eq), and smog potential (kg O_3-eq) were calculated using TRACI 2.1 impact estimators. Cumulative energy demand (primary energy) (MJ-eq), including both the biomass and fossil fuel contributions, were calculated and reported directly from LCI flows. The present study tracked fresh water consumption (in L) and renewable and non-renewable material resource consumption (non-fuel resources). Impact categories and other impact measures were reported on a 100 ft^2 (9.29 m^2) and m^3 basis.

An EPD of redwood decking may be developed based on the results obtained in this LCA project (FPInnovations 2011). Therefore, the following additional environmental information was derived from the LCA flows in accordance with ISO 21930 Clause 8.2 (ISO 2007):

1. Generation of waste
2. Emissions to water, soil, and air

3.7 Interpretation

In conducting the LCIA, the present study did not go beyond the mid-point impact categories highlighted in ISO 21930 (ISO 2007). End-point impact categories will not be calculated because of their higher level of uncertainty compared to the mid-point categories. The LCI flows were converted to the above impact categories according to TRACI 2.1 method found in SimaPro 7 (PRé Consultants 2013). Carbon storage in the final product was included as part of the life cycle for redwood and WPC decking. Additionally, see Section 5.4.1.6 for redwood decking calculations on carbon sequestration. These calculations helped develop the carbon balance for redwood decking.

3.8 Assumptions

- Specific gravity, density, and other physical properties of redwood (*Sequoia sempervirens*) were sourced from Alden (1997), Jones and O'Hara (2012), and Miles and Smith (2009).
- Redwood decking was assumed to equilibrate at 12% moisture content (MC[4]) after installation. Green redwood logs, however, were 127% MC and heartwood was 100% MC.
- Redwood decking includes both pure heartwood and a mixture of heartwood and sapwood (Piitro 1986; Highley 1995; Jones et al. 2011). Redwood decking is not pressure-treated because it is mostly heartwood.
- 38- × 140-mm (2- × 6-in) redwood decking weighs 1,400 pounds per MBF.
- Using higher heating values (HHV), this study converted fuel from its volume or mass basis to its energy value. HHV represents the (gross) energy content of a fuel with the combustion products at 25°C (77°F) with all water vapor brought to liquid form. Whereas lower heating value (net energy) maintains the water in the combustion product in vapor

[4] Moisture content (MC) is calculated on a dry basis. $MC = \frac{Mass\ of\ water\ in\ wood}{Oven\text{-}dry\ wood\ mass} \times 100\%$.

form at 150°C (302°F). HHV instead of lower heating values is the preferred method in the United States to calculate energy values (EIA 2013).

3.9 Value Choices and Optional Elements

Optional LCIA steps such as normalization, grouping, and weighting were not completed. End-point impact categories such as Eco-Indicator 99 were not used because of their higher level of uncertainty as compared to the mid-point categories reported using the TRACI method. The LCA analysis, particularly at end-of-life, was chosen to be as consistent as possible to the other decking materials to allow for an objective comparison.

3.10 Limitations

3.10.1 *Omissions of life-cycle stages, processes, input or output flows*

Human labor and the manufacturing LCA of machinery and infrastructure, including logging roads, was outside the system boundaries and therefore not modeled in this analysis.

3.10.2 *Decision Criteria (cut-off rule, if applicable)*

All materials used in the logging and manufacturing process that have a significant environmental impact were tracked. For the present study, mass and energy that contributed less than 1% to the total output were not modeled in the SimaPro LCA software. Initially, all LCI flows were included in the impact categories. The final analysis included any mass or energy resource that resulted in a greater than 2% change to any impact category.

3.11 Data Quality Requirements

(1)Time-related coverage, (2) geographical coverage, (3) technological coverage, (4) representation, and (5) sources of data: Primary data for redwood decking was collected for raw material extraction (i.e., harvesting) and product manufacturing for 2010 and 2011 on an annual basis from redwood operations in northern California. Additional LCI data on decking materials was drawn from the externally reviewed LCA report of Mahalle and O'Connor (2009) and Franklin Associates (FAL) (2010) and peer-reviewed literature such as Bolin and Smith (2011). Secondary data from other life-cycle inventory (LCI) databases was used in the following order of preference: US LCI Database (USDA 2012) and the U.S. version of the European database EcoInvent (www.ecoinvent.ch) referred to as US IE.

The four redwood mills included in this study are members of the CRA, who sponsored the study. These mills located in California are in Davenport, Scotia, Korbel, and Ukiah. The four mills produced about 90% of redwood decking manufactured in the United States in 2010. One redwood mill did not kiln-dry their decking but the other three redwood mills did some kiln–drying.

(6) Precision: To aid in validating the data precision, the present study surveyed a minimum of 50% of redwood production in the United States. According to the USDOC (2011) and Binam (2013), twelve redwood mills produced 614 thousand m3 (260 million board feet (bf)). Thus, to meet the data requirement, approximately 308 thousand m3 of redwood production was to be surveyed from a minimum of four sawmill facilities. In 2010, the annual production of the four California redwood mills surveyed was 552 thousand m3 (260 million bf). This represented approximately 90% of the total rough green redwood lumber production in the US. Individual

mill production ranged from 44.4 to 238 thousand m3 (18.8 to 101 million bf) of rough green lumber. The data collectors gathered process-specific data on-site wherever possible.

(7) Completeness, (8) Uncertainty, and (9) Consistency: Measures of completeness and uncertainty were provided, including a listing of study limitations and assumptions. To deal with potential unknowns, sensitivity and scenario analyses were conducted to address these issues as necessary. A mass balance, from material input to material output for the sawmill, energy comparison to other wood products, and a sensitivity analysis were conducted to address uncertainty in data quality. Redwood sawmills reported primary data for the whole sawmill on an annual basis.

(10) Reproducibility: Questionnaires were used to survey the redwood operations to collect primary data on both timber harvesting (**APPENDIX 13)** and lumber manufacturing. (**APPENDIX 14)**. The primary data obtained from the surveys were weight-averaged using the formula shown below (Milota et al. 2004):

$$\bar{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

Where $\bar{P}_{\text{weighted}}$ is the weighted average of the values reported by the sawmills, P_i is the reported sawmill value, and x_i is the fraction of the sawmill's value to total production of the surveyed mills for that specific value. The cradle-to-gate LCI flows for the four decking materials were provided in a separate attachment titled "Cradle-to-grave LCI flows of four decking products".

3.12 Peer Review

For maximum credibility and transparency, the analysis and results were subject to an independent peer review panel organized by Wayne Trusty (Wayne B. Trusty & Associates Limited; Merrickville, ON,, Canada, Tel: (613) 269-3795, e-mail: wbtrusty@sympatico.ca) who served as the Panel Chair. The other panel members were Getachew Assefa Wondimagegnehu, Associate Professor at the University of Calgary and Athena Chair in Life Cycle Assessment in Design, and Gary Rynearson, Forest Policy Manager of Green Diamond Resource Company.

3.13 Electrical Grids

Table 3-2 provides the location and regional grids used in SimaPro to model the environmental impacts from using grid electricity. The electrical grid is broken into 26 regions of the United States[5].

[5] eGrid: http://cfpub.epa.gov/egridweb/ghg.cfm.

Table 3-2: Regional grids in SimaPro for decking production

Process	Location	Grid	Comments
PVC resin production	Louisville, KY	SRTV 2008	
PVC decking production	Columbus, OH	RFCW 2008	
Virgin HDPE resin production	Fort Worth, TX	ERCT 2008	50% of total production
Virgin HDPE resin production	Magnolia, AR	SRMV 2008	50% of total production
Planer shavings	Pacific Northwest	NWPP 2008	
Recycled HDPE pellets	Fernley, NV	NWPP 2008	Local pellet production
WPC decking production	Fernley, NV	NWPP 2008	
Redwood production region	Upper northern CA	NWPP 2008	50% of total production
Redwood production region	Lower northern CA	CAMX 2008	50% of total production

4 Cradle-to-Gate Life-Cycle Inventory Data

This section covered the life cycle of decking products from resource extraction to creation of final product at mill gate.

4.1 Polyvinyl Chloride

The cradle-to-gate LCI data for PVC decking was developed using existing LCI and production-related data including a 2009 decking and siding report (Lippiatt 2007; Mahalle and O'Connor 2009; Trex 2009; FAL 2010). PVC decking formulation was based on the assumption that siding and decking manufacturing processes were similar. No PVC resin plants exist in California[6].

TimberTech XLM decking is a major seller of PVC decking into the West Coast, therefore their product was used to represent PVC decking in this study. TimberTech XLM decking is made in Columbus, OH[7]. As for the manufacturing of PVC resin, the primary component (82.5%) of PVC decking, the closest plant to Columbus, OH, was located in Louisville, KY (325 km). Resource transportation was based on hauling the PVC resin from Louisville to Columbus by diesel tractor-trailer. **Table 4-1** lists the ingredients for the production of one metric ton of PVC decking (Lippiatt 2007). One metric ton of PVC decking corresponds to 640 ft^2 (59.5 m^2) of installed decking (156 kg/100 ft^2). **Table 4-2** lists the energy resources used during the extrusion process derived from the US EI database to make one metric ton of PVC decking.

Table 4-1: Resource list for manufacturing one metric ton of polyvinyl chloride decking (Lippiatt 2007; Mahalle and O'Connor 2009)

Ingredients	Amount	Unit	Percent	Database
PVC resin	825	kg	82.5	US LCI
Filler (calcium carbonate)	85	kg	8.5	US LCI
Titanium dioxide	25	kg	2.5	US LCI
Impact Modifier (acrylic or chlorinated PET)	40	kg	4.0	US LCI
Stabilizer (organo-tin mercaptide)	10	kg	1.0	US EI
Lubricant (parrafin/calcium stearate)	15	kg	1.5	US EI

[6] EPA to regulate PVC plant emissions http://earthjustice.org/features/epa-to-regulate-pvc-plant-emissions .
[7] Personal communication on 01/18/2012, TimberTech Live Chat.

Total	1000	kg	100

Table 4-2: Energy resources required to produce one metric ton of PVC decking (Lippiatt 2007; Mahalle and O'Connor 2009)

Plastic extrusion energy inputs	Unit	Amount	Database
Electricity	kWh	508	US LCI
Natural gas	MJ	121	US LCI
Heavy fuel oil	MJ	683	US LCI

4.2 Wood–plastic Composite (virgin and recycled)

The manufacturing process was comprised of two parts: raw material preparation and extrusion. For WPC decking, wood flour and HDPE made up the primary ingredients and include some ancillary materials as shown in **Table 4-3** and Error! Reference source not found. (Mahalle and O'Connor 2009; Bolin and Smith 2011). At 50%, wood flour was the largest ingredient in making WPC decking. In addition, because the WPC decking was 50% wood (i.e., wood flour), carbon uptake during tree growth was considered. A carbon storage value of 917 kg of CO_2 per metric ton of final product[8] was calculated. The CO_2 stored in the final product was given a characterization factor of –1 when calculating GWP. Note that no existing LCI data exists for maleated polyolefins. Therefore, a 50:50 mix of HDPE (10 kg/metric ton decking) and acetic acid formulation (10 kg/metric ton decking) was used as a proxy.

Table 4-3: Resource list for manufacturing one metric ton of wood–plastic composite decking (Mahalle and O'Connor 2009)

Ingredients	Mass (kg)	Percent	Database
Wood flour	500	50	US LCI
PE (virgin and reprocessed)	400	40	US LCI
Talc	20	2	US EI
Polyester resin (lubricant)	20	2	US EI
Borax (Biocide-borate)	20	2	US EI
Titanium dioxide	20	2	US LCI
Acetic acid (coupling agents-acid 50%)	10	1	US LCI
HDPE resin (coupling agent-PE)	10	1	US LCI
Total	1000	100	

Table 4-4: Ancillary list for producing one metric ton of virgin wood–plastic composite decking (Mahalle and O'Connor 2009)

Lubricating oil (motor oil; assume 1 kg/l)	0.012619054	Kg	US EI
Lubricating oil (grease)	7.94E-07	Kg	US EI
Diesel oil	.0968	L	US LCI

4.2.1 *Raw Material Preparation*

As shown in **Table 4-3**, wood flour from planer shavings and PE resin were the two main components in WPC decking. Wood flour production includes the transport of planer shavings

[8] 500 kg wood/metric ton WPC × 0.5 kg carbon/1.0 kg wood × 44 kg CO_2/12 kg carbon = 917 kg CO_2/metric ton.

from the softwood sawmill to the WPC decking plants, the grinding of planer shavings to a flour consistency using hammermills and pre-drying of wood flour before mixing with the PE resin. Environmental burdens assigned in producing wood flour from planer shavings used in making WPC decking were consistent with previous decking LCA studies (Mahalle and O'Connor 2009; Bolin and Smith 2011). Wood flour was stored in a silo. Softwood mills, providing planer shavings, were 1,200 km from the decking manufacturing facility located in Fernley, NV. Trex (San Jose, CA), a large WPC decking manufacturer, has a plant located in Fernley, NV, that supplies both virgin and recycled WPC decking to the western United States. Therefore, Trex WPC decking was the virgin and recycled WPC decking analyzed in the present study.

For virgin HDPE resin, the nearest HDPE plants were located in Fort Worth, TX, and Magnolia, AR; therefore, an average transport distance of 4,400 km was calculated. For reprocessed LDPE going into recycled WPC decking, the raw material consisted of bailed clean and dry grocery plastic sacks. Dirty grocery plastic sacks require washing and drying (a process that consumes considerable energy). It is assumed that enough clean and dry plastic sacks were available within an average transportation distance of 250 km and that the mode of transportation was a single unit truck. Therefore, no washing and drying occurred. The weighted average raw material transportation for all raw materials was based on the transportation distance of wood planer shavings (1,200 km), either virgin or reprocessed PE resin, and the additives (70 km). Virgin HDPE resin was assumed to be mostly transported by rail (80%) and the remaining distance by diesel tractor-trailer truck (20%) because of the long distance between the HDPE resin plant and the WPC decking plant.

WPC decking was made from either 100% virgin HDPE or 100% reprocessed LDPE. The only product from the plants is WPC decking. Therefore, all LCI flows were assigned to the decking. Reprocessed LDPE was located considerably closer to the decking plant than virgin LDPE. Only clean and dry plastic LDPE sacks were used in making the 100% recycled content WPC decking. Therefore, careful handling of the plastic grocery sacks was necessary to prevent re-contamination of the dry and clean bags that would have had added additional processing. **Figure 4-1** details the handling processes for preparing LDPE bags before the extrusion process. The bailing process compacted the clean and dry bags for easier handling, transporting, and processing upon arrival at the WPC decking plant.

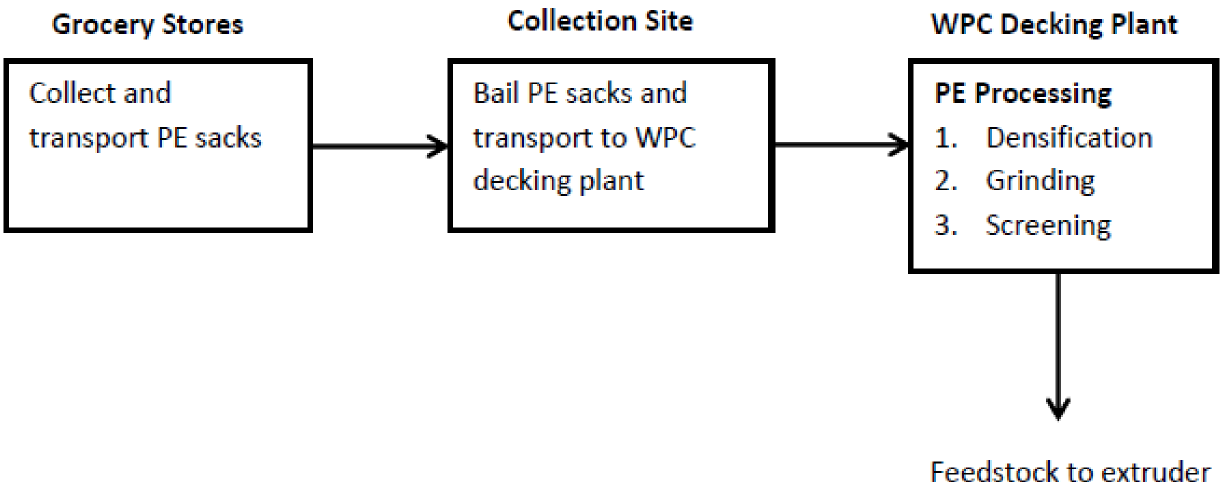

Figure 4-1: Stages of processing for LDPE bags (Climenhage 2003).

4.2.2 *Wood–plastic Composite Processing*

Additional processing of the material inputs occurred at the WPC decking plant. Grinding the planer shavings into wood flour included both a grinder and a dust collection system. Hammermills ground the wood flour to a 20- to 60-mesh size. A conveyor system transported the wood dust collected from the grinding process to a silo for processing into the WPC decking (LDED 2005). A second silo contained the PE resin.

The extrusion process involved blending the wood flour with the PE resin along with the other ingredients. Additional manufacturing processes included profiling the decking along with cooling, sizing, and surfacing. The largest impacts associated with the extrusion process were from energy consumption. Wood fiber drying, blending/compounding, profiling the extrusion and other downstream processes consumed substantial amounts of energy. Other air emissions included CO_2 from wood fuel and minor emissions from the polymers as well as emissions from the venting process associated with the biocide (Borax). Fugitive emissions were less than 1% of the total and therefore not included in the LCA. Electricity was the primary energy source for the extrusion process (Mahalle and O'Connor 2009).

A common practice during WPC decking manufacturing is for the WPC decking waste generated on-site during the product manufacturing process (e.g., from defective decking at the production facility) to be reground and added back into the raw material mix. Regrind amounts typically add up to 5–10% of the mix (LDED 2005). In the current project, a pair of hammermills reground the defective material to 1/8-inch particle size. For the grinding dust, a collection system gathered the fugitive wood dust and mixed it back into the process.

4.2.3 *Process Energy*

Electricity was the main energy consumed during WPC decking production, from a cradle-to-gate perspective. In the 2009 LCA report by Mahalle and O'Connor, the extrusion process consumes 1,420 kWh/metric ton of decking produced. The US LCI Database has a unit process called "recycling HDPE postconsumer pellets" that consumes 490 kWh/metric ton. Both values are listed in **Table 4-5**. For wood flour manufacturing, the hammermills consumed 58 kWh/metric ton to produce 40-mesh wood flour from dry planer shavings.

Table 4-5: Electrical energy consumed for the two main unit processes

Category	Unit process	Amount (kWh/tonne)[1]	Database
Raw material processing	Wood flour manufacturing[3]	58	US LCI
	Recycled HDPE pellets[2]	490	US LCI
WPC manufacturing	Extrusion process[3]	1,420	US LCI
	Regrinding[3]	6	US LCI

[1] WPC decking is 2.27 metric tons/ thousand bf (2.50 tons/thousand bf).
[2] US LCI Database process.
[3] Brown (2008); Goertermiller (2012); Bolin and Smith (2012); Mahalle and O'Connor (2009).

4.3 Redwood

4.3.1 *Forest Resources*

Redwood is a unique species growing naturally along the coastal area of northern California. The primary source of data used for this study was collected from four redwood forest products companies in northern California. The four mills represented 83% of redwood decking product production in 2010. A survey questionnaire in **Appendix 13** was developed to collect forest resource management data. Questions related to log volume in MBF harvested through the rotation age of the forest stand were also in the survey. The survey was completed based on the 2010 calendar production year. These data were combined with information from the existing literature and personal interviews. An overall forest management scenario and assumptions used for the analysis of the present study are outlined in **Table 4-6**, **Table 4-7**, and **Table 4-8**.

4.3.1.1 Survey Data Including Assumptions

The survey data were aggregated and summarized to calculate weighted average values that represent a mean value for each category of interest. Weights were based on each company's annual harvest volume, silvicultural methods (i.e., even-age or thinning/selection), and harvesting systems used (**Figure 4-2**). The data summary and initial calculation values were entered into the harvest factors spreadsheet that was developed for prior CORRIM reports detailing LCA and LCI for wood products in the United States (Johnson 2008). The harvest factors spreadsheets integrate stand establishment, intermediate treatment, timber harvest, and transportation factors into a presentation of total cost, fuel and oil consumption rates, and carbon footprint associated with wood removal and equipment used.

Table 4-6: Assumptions and input values used for the environmental impact analysis of redwood forest[1]

	Thinning/Selection	Even-age[2]
Seedling planting density (trees per ha)	432 (175 per acre)	319 (129 per acre)
Fertilization to trees	None	None
Harvest volume (% total)	47	53
Harvest volume (m^3/ha) per entry	100[3,4] (7.41 MBF/acre)	300[3,4] (21.81 MBF/acre)
Harvest unit size (ha)	14.2 (35 acre)	10.1 (25 acre)
Age of trees (years)	40-100+	60

[1]Estimate of bark as percent of solid wood: 9.9% after accounting for handling losses
Average skidding/yarding distance: 202 m (663 feet) for all harvesting systems used
One-way log hauling distance: 53.1 km (33 miles) in average
Specific gravity (green): 0.36 (Miles and Smith 2009).
Carbon fraction (mass carbon per unit mass dry wood): 0.53 (Jones and O'Hara 2012).
[2]Even-age results were compiled from responses for clearcut harvesting systems on the survey form.
[3]Thinning/selection enters every 20-year to harvest 7.41 MBF/acre.
[4]Based on a conversion factor of 190 ft^3/MBF (Fonseca 2005); 35.3145 ft^3/m^3; 2.47 ac/ha.

Table 4-7: Fertilization rates to grow coast redwood two-year old seedlings

Fertilization[1]	Nitrogen (N)	Phosphate (P)	Potassium (K)
(kg/ha)	0.137	0.125	0.208
(kg/seedling)	0.00100	0.00091	0.00151

[1] The values of lb/acre are based on the planting rate of 137 seedlings per acre of forestland (2.205 lb/kg; 2.47 ac/ha).

Table 4-8: Fuel and lubrication consumption rate for tree planting and pre-commercial thinning

	Gasoline (L/ha-km[1])	Lubrication (L/ha-km[1])
Tree planting	0.00386	0.000069
Pre-commercial thinning/selection	0.00649	0.000118

[1]Distance from a seedling storage place to a planning site.

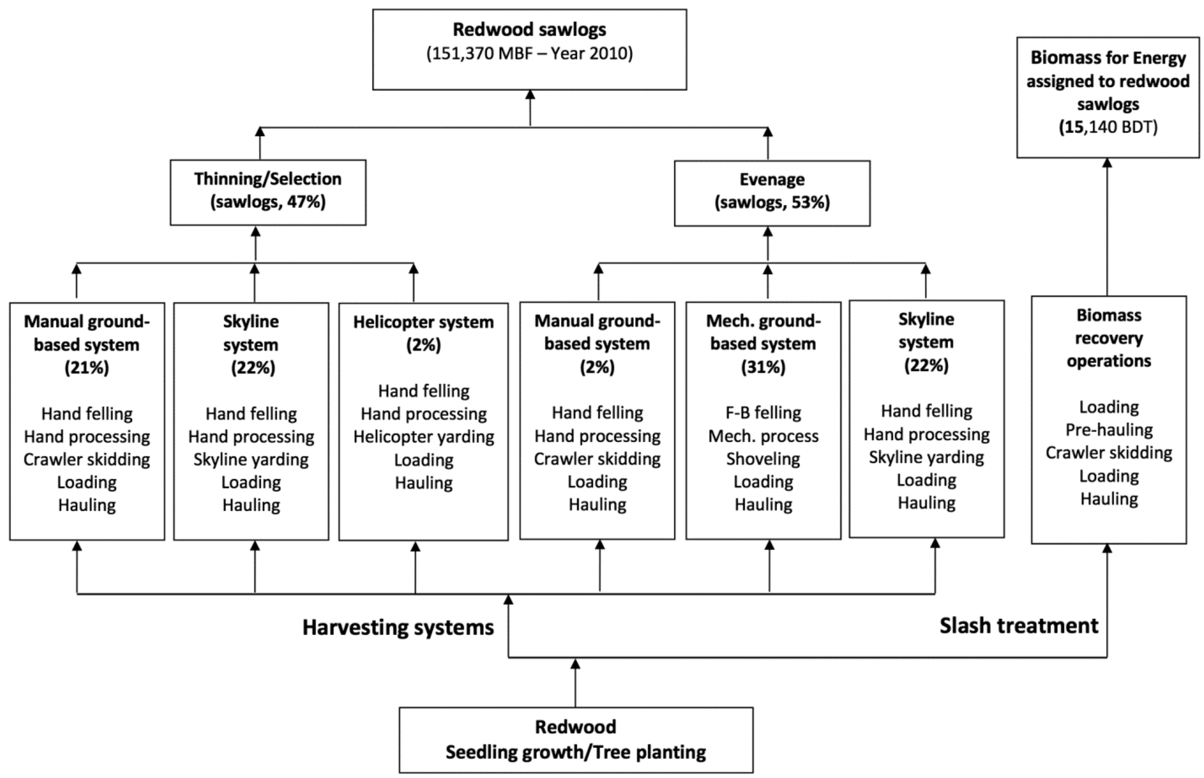

Figure 4-2: Redwood forest operations producing saw logs and biomass.

SimaPro 7.3 LCA modeling software (PRé Consultants 2013) estimated environmental outputs to the air and water from the redwood forest management activities from weighted-average survey data. The first step was to develop the redwood resource database within the SimaPro program. The information that was summarized in the harvest factors spreadsheet was entered into SimaPro based on a cubic meter (saw logs), a bone-dry metric ton (biomass), or a per-hectare basis (reforestation).

Key input values entered include fuel/oil consumptions and volume removed/acre for six different harvesting systems and two silvicultural methods (**Table 4-9**). Each harvesting system consisted of a set of machines that are commonly used to harvest redwood saw logs in northern California and consumed different amounts of fuels and lubricants. The survey questions were structured into four categories: stand establishment and forest inventory, harvesting systems and productivity, log transportation, and slash treatments and biomass recovery for energy. Under each category, survey questions were asked to describe forest management activities and resources that were required to produce redwood logs.

Table 4-9: Hourly productivity and fuel and lubricant use of redwood harvesting systems[1]

			Machine type	Production rate (m³/hour)	Fuel use[2] (L/m³)	Lubricant use[2] (L/m³)
	Manual ground-based system					
Thinning/ Selection		Felling	Chainsaw	5.30	0.505	0.0091
		Skidding	Tracked crawler	7.15	6.894	0.1241
		Processing	Chainsaw	13.60	0.102	0.0018
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			9.46	01.70
	Skyline system					
		Felling	Chainsaw	5.30	0.505	0.0091
		Yarding	Skyline yarder	9.93	6.363	0.1145
		Processing	Chainsaw	13.60	0.102	0.0018
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			8.93	0.161
	Helicopter system					
		Felling	Chainsaw	5.30	0.505	0.0091
		Yarding	Helicopter	37.93	34.885	0.6279
		Processing	Chainsaw	13.60	0.102	0.0018
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			37.46	0.674
	Manual ground-based system					
Even-age		Felling	Chainsaw	6.03	0.665	0.0120
		Skidding	Tracked crawler	12.11	4.412	0.0794
		Processing	Chainsaw	18.93	0.077	0.0014
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			7.12	0.128
	Mechanized ground-based system					
		Felling	Feller-buncher	38.85	1.734	0.0312
		Yarding	Shovel	19.37	3.392	0.0611
		Processing	Stroke-boom delimber	38.74	1.551	0.0279
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			8.64	0.156
	Skyline system					
		Felling	Chainsaw	6.03	0.665	0.0120
		Yarding	Skyline yarder	12.81	4.727	0.0851
		Processing	Chainsaw	18.93	0.077	0.0014
		Loading	Log loader	22.87	1.964	0.0354
		System total (stump-to-truck)			7.43	0.134
	Landing to Intermediate Load Site				(L/mBDT[3])	(L/BDT[3])
Biomass recovery operation		Loading:	Loader	30.41	0.718	0.0129
		Pre-hauling:	Dump truck- modified	13.82	0.936	0.0169
	Centralized grinding					
		Loading:	Loader	30.41	0.718	0.0129
		Processing:	Horizontal grinder	27.21	3.685	0.0663
		System total (stump-to-truck)			6.06	0.109

[1] The values presented in this table were based on each entry to the redwood stand to harvest redwood saw logs and logging slash for the year of 2010.

[2] Included machine idling time (i.e., scheduled machine-hour, SMH).

[3] Bone dry metric ton.

4.3.1.2 Stand Establishment and Forest Inventory.

This section of the survey requested information on stand establishment and an overview of redwood forest management plan and activities. Survey results provided information used to outline a framework of forest management practices that are commonly used by redwood forest products companies. Information collected included nursery operations, seedling planting activities, intermediate treatment activities (fertilization and pre-commercial thinning), silvicultural systems used, rotation ages, and volume removed each entry.

4.3.1.3 Harvesting Systems and Productivity.

This section of the survey asked for descriptions of typical harvesting systems and equipment used to harvest timber from stump to truck, including felling, primary transport (stump-to-landing), processing, and loading (**Table 4-9**). Three major types of harvesting systems were surveyed: ground-based, skyline, and helicopter.

These three harvesting systems were further divided based on equipment type used and silvicultural methods (i.e., thinning/selection, even-age) applied. **Figure 4-2** shows the percentage of the six harvesting system that provided the 814,405 m^3 (151,370 MBF) of redwood logs in 2010 and adds up to 100%.

In addition, survey questions were related to harvesting productivity (i.e., MBF/hour), cost ($/MBF), and fuel/oil consumption rates for each harvesting equipment used. Additionally, machine utilization rates were surveyed to adjust hourly productivity and fuel/oil consumption rates.

4.3.1.4 Log Transportation.

Log transportation started from the forest landing in the woods, included loading at the landing and unloading at the sawmill. Log transport was allocated to the manufacturing process that is consistent with other CORRIM research.

4.3.1.5 Slash Treatments and Biomass Recovery for Energy.

The survey also requested a description of activities for managing slash resulting from timber harvest. It included data on percent utilization of trees cut, prescribed burning and biomass recovery operations for energy production (**Figure 4-2**). Operations productivity (i.e., ton/hour) and fuel/oil consumption rates were collected for biomass recovery equipment and systems that are commonly applied to utilize forest residues left from redwood saw log harvesting (**Table 4-9**). Biomass recovery operations are relatively new to this region, but there has been an increasing interest in utilization of logging slash. For redwood logging slash, 48% of the total collected, 13,730 bone dry metric tons (15,140 tons) was delivered to local energy plants in 2010.

4.3.1.6 Carbon Sequestration Calculation

Trees, the raw materials for wood products sequester carbon during its growth through photosynthesis, a natural process. Therefore, this study looked at the impact of carbon sequestration into the analysis by tracking the carbon uptake into the logs. The following calculations were performed to help develop a carbon balance on redwood decking. As previously mentioned, GWP did not include biogenic CO_2 emissions to be consistent with

TRACI 2.1. However, GWP in this study did include the carbon stored in the final product to be consistent with the revised North American wood product Product Category Rule (PCR). The analysis was broken into the two forest management practices (even-age and thinning/selection). By production volumes, even-aging was 53% of total with thinning/selection covering the remaining 47% as shown in **Table 4-6**. A weighted-average approach for the different practices was used for forest operations as shown by **Figure 4-2**. To aid in tracking both wood mass and carbon flow for the rest of the life cycle, the logs were broken into roundwood and bark. Percentage of roundwood (90.1%) and bark (9.9%) were from weight-averaged primary data collected at the sawmill. The following equations calculated the carbon sequestration values for the surveyed redwood forest removals for 2010 per hectare:

<u>Even-age (kg/hectare):</u>
Carbon uptake factor (i.e., CO_2 equivalent) for round wood
= wood volume per Ha × specific gravity × 1000 × CO_2 uptake factor x carbon content of wood
= 290.17 m^3 per Ha × 0.36 × 1000 × (44/12) x 0.53 = 203,003 kg CO_2-eq per Ha

Carbon uptake factor (i.e., CO_2 equivalent) for bark
= volume of bark × specific gravity ×1000 × CO_2 uptake factor × carbon content of wood
= 32.50 m^3 per Ha × 0.36 × 1000 × (44/12) x 0.53 = 22,737 kg CO_2-eq per Ha

<u>Thinning/selection (kg/hectare):</u>
Carbon uptake factor (i.e., CO_2 equivalent) for round wood
= 100.13 m^3 × 0.36 × 1000 × (44/12) x 0.53 = 70,051 kg CO_2-eq per Ha
Carbon uptake factor (i.e., CO_2 equivalent) for bark
= 11.21 m^3 × 0.36 × 1000 × (44/12) × 0.53 = 7,842 kg CO_2-eq per HA

Where

- Specific gravity = 0.36 of green specific gravity when logs harvested
- 1000 = converting from specific gravity to a unit of kg/m^3
- CO_2 uptake factor = the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom (44:12; EPA 2005)

4.3.1.7 Logging Slash Recovered for Power

Recovering slash helps reduce fire hazard and site preparation costs as well as avoid slash burning. Weight-averaging survey data calculates 16.9 oven-dry (OD) kg redwood logging slash fuel per m^3 of harvested redwood log. Based on power plant reported volume and energy production, one OD kg of wood fuel generates approximately 1.14 kWh (20% electrical conversion of electricity out to wood fuel in). Logging slash typically degrades naturally on the forest floor or is burned in the forest emitting biogenic CO_2 thus becomes part of the natural carbon cycle. No scientific consensus has been developed to incorporate the impact of logging slash when burned to generate electricity once the stem has been removed for processing. Likely, the power plant burning the logging slash would be accountable for the collection and transportation data while given credit for the electricity generated to avoid regional grid electricity. Therefore, this LCA did not include any positive or negative environmental burdens pertaining to logging slash.

4.3.2 *Resource Transportation*

Transportation of redwood logs cut from the trees occurs by logging trucks. Logging trucks collect the redwood logs (127% MC) at the landing and transport the logs an average of 54 km to the sawmill log yard. No other material transported to the mill was greater than 1% of the mass of the incoming logs. Therefore, no other material transportation data besides logs were included in the LCA.

4.3.3 *Product Production*

Typical sources of energy consumed during the manufacturing process include thermal energy for kiln–drying the decking and electrical energy for log breakdown into decking and other co-products.

4.3.3.1 Material Flow

Figure 3-7 illustrates the unit processes for redwood product manufacturing, starting with the log yard operations. Diesel logging trucks unload the redwood logs into the log yard. Log storage occurs year round although the log volume depends on the season. Sawmills typically stockpile logs during the dry season when logging conditions are optimal. Redwood mills track log volume to ensure there is an adequate volume of logs to keep the mill operating. Two of the four redwood mills surveyed sprinkle their logs with water to maintain freshness and keep the logs from checking and splitting. Fork lifts powered by diesel, gasoline, and propane (natural gas is a proxy) move the logs around the yard and to the sawmill for debarking and further processing. Bark comprises about 9.9% of the incoming log volume. After debarking, the log is sawn into rough lumber. The sawing process (minus the bark) produces rough green decking (59.9%), wood chips (22.7%), sawdust (9.5%), hog fuel (5.0%), and shavings (1.9%). The three processing options for rough green decking include 1) planing and selling as green decking (7.6%), 2) selling as is (28.4%), or 3) drying and selling as dried decking (64.0%).

Drying rough green decking usually occurs by first air-drying and then kiln-drying to reach the desired MC. Drying redwood decking lowers the total weight of the board. In addition, drying reduces the volume of each board once the board dries below the fiber saturation point although the mass of wood per board stays constant. Sawmills have to consider wood shrinkage when sawing the logs into green lumber. The vast majority of redwood decking is sold as dry planed decking product (62.4%), whereas only 2.6% rough redwood decking is sold.

As part of the process of confirming the data quality, a mass balance was performed and the results are summarized in **Table 4-10**. In performing the mass balance for redwood decking, all the unit processes located within the site system boundary were considered. Using a weight-averaged approach, 648 OD kg of incoming redwood logs with a green density (127% MC) of 803 kg/m^3 produced 1.0 m^3 (380 OD kg) of planed redwood decking. The sawing process yielded 388 kg of rough green decking with no loss of wood substance occurring during the drying process. Planing the rough lumber into a surfaced decking product reduced the 388 OD kg of rough dry decking to 380 OD kg of planed dry redwood decking, for a 2% reduction in mass. Some of the wood waste was converted on-site to thermal energy in a boiler. Boilers burned all 8 OD kg of dry shavings produced onsite for thermal process energy. Overall, an average log was reduced to 59% (380/648) of its original mass during its conversion to planed dry redwood decking.

According to the North American PCR, if the mass/energy of a flow is less 1% of the cumulative mass/energy of the model flow it may be excluded, provided its environmental relevance is minor. This analysis included all energy and mass flows for primary data (FPInnovations 2011).

Table 4-10: Mass balance of manufacturing redwood decking

	Sawing process		Boiler process	Dryer process		Planer process		All processes combined		
Material (OD kg)	In	Out	In	In	Out	In	Out	In	Out	E
Green logs (wood only)	648	—	—S	—	—	—	—	648	0	–648
Green logs (bark only)	71	—	—	—	—	—	—	71	0	–71
Green chips	—	147	—	—	—	—	—	0	147	147
Green sawdust	—	68	—	—	—	—	—	0	68	68
Green bark	—	71	—	—	—	—	—	0	71	71
Green shaving	—	12	—	—	—	—	—	0	12	12
Green hog fuel	—	32	—	—	—	—	—	0	32	32
Rough green decking	—	388	—	388	—	—	—	388	388	0
Rough dry decking	—	—	—	—	388	388	—	388	388	0
Planed dry decking	—	—	—	—	—	—	380[1]	0	380	380
Dry shavings	—	—	8	—	—	—	8	8	8	0
Sum	719	719	8	388	388	388	388	1503	1495	–8

[1] Equal to one cubic meter of redwood decking.

4.3.3.2 Carbon Balance

Table 4-11 shows the carbon flow for redwood decking from carbon uptake during sequestration to production of the final product. As indicated, 262 kg CO_2-eq/100ft^2 (738 kg CO_2-eq/m^3) was stored as carbon in the final product. In comparison, virgin and recycled WPC decking stored 244 kg CO_2-eq/100ft^2 as these products were 50% wood. As noted previously, WPC decking is substantially denser than redwood decking. Therefore, even though WPC decking is only 50% wood, WPC stores about the same value of carbon as redwood decking on a per functional area basis. As done for WPC decking, the carbon stored in redwood decking was given a characterization factor of –1 when calculating GWP. Carbon uptake was developed from the wood mass balance for a cubic meter of redwood decking provided in **Table 4-10**[9].

[9] (648+71.5) kg wood in /m^3 redwood decking out × 0.53 kg C/kg wood × (44 kg CO_2/kmole) ÷ (12 kg C/kmole) = 1,398 kg CO_2-eq/m^3 redwood decking out.

Table 4-11: Carbon balance of redwood decking

Carbon flows per unit of redwood decking made	(kg CO_2-eq/100 ft^2)[1]	(kg CO_2-eq/m^3)
Carbon uptake	–495	–1398
Mill residue combusted on-site for on-site thermal energy	5	16
Mill residue leaving site and combusted for electricity (71%)	162	457
Mill residue leaving site and decayed as soil amendment (25%)	57	161
Mill residue leaving site and made into new wood product (4%)	9	26
Carbon stored in final product	262	738
Balance	0	0

[1] 0.354 m^3 per 100 ft^2 redwood decking.

4.3.3.3 Energy Consumption

Redwood decking production required both electrical and thermal energy for processing the logs into the decking. For the four mills surveyed in this study, most thermal energy was produced onsite. However, some steam was produced nearby and piped to the mill. Electricity was obtained off-site from the combined NNWP/CAMX power grids (50/50). Electrical energy was required for the log yard operations, sawing, drying, and planing unit processes, whereas thermal energy was only used during the drying process.

Survey results showed that 222 MJ[10] of unallocated process energy was consumed per cubic meter of redwood decking produced. The total unallocated electrical consumption, not including primary energy, was 91 kWh/m^3 of final product (**Table 4-12**). Primary energy refers to the energy embodied in natural resources such as fossil fuels in ground and biomass in trees before being converted into electricity or heat. For the log yard operations, sawing, drying and planing, the consumption of the grid electrical energy was 1.1%, 67.7%, 10.7%, and 20.5% of the total, respectively. Based on this breakdown, the four unit processes used 1.0, 61.9, 9.8, and 18.7 kWh of grid electricity per m^3 of redwood decking produced. The major sources of process energy were from the wood fuel generated onsite from the planing process, from natural gas, and from piped-in steam produced from burning wood biomass off-site.

Total electrical energy consumption per cubic meter of redwood decking produced is comparable to the published western redcedar decking (*Thuja plicata*) value of 118 kWh/m^3 (Mahalle and O'Connor 2009). In addition, the electrical consumption for producing planed dry redwood decking was found to be similar to NE/NC United States softwood lumber where the value was 99 kWh/m^3 (Bergman and Bowe 2010). These values do not include primary energy resources. **Table 4-13** tracked the ancillary material consumed during the decking manufacturing process and the amounts of these materials.

[10] (8.05+1.86)OD kg wood*20.9MJ/OD kg wood+0.375 m^3 natural gas*54.4 MJ/kg*0.705kg/m^3=222 MJ/m^3 redwood decking.

Table 4-12: Material and energy consumed on-site to produce redwood decking (SimaPro input values). Includes fuel used for electricity production and for log and transportation (unallocated)

Fuel type	Quantity	SI Units per m^3	Quantity	Units per MBF[1]
Fossil fuel				
Natural Gas[2]	0.375	m^3	0.023	1000 ft^3
Electricity				
Grid (eGrid)	91	kWh	158	kWh
On-site transportation fuel				
Off-road diesel	2.43	L	15.9	Gal
Gasoline	0.36	L	2.3	Gal
Propane	0.10	L	0.6	Gal
Renewable fuel				
On-site Wood Fuel[2]	8.05	Kg	30.7	Lb
Off-site Wood Fuel[2, 3]	1.86	Kg	7.1	Lb
Water use				
Surface water	187	L	1220	Gal
Ground water	22	L	146	Gal

[1] 1.73 m^3 per 1.0 nominal thousand board feet planed redwood decking.
[2] Energy values were found using their HHV in MJ/kg; 20.9 MJ wood oven-dried and 54.4 for natural gas.
[3] Wood boiler producing steam at a nearby facility.

Table 4-13: List of ancillary materials consumed during manufacturing

Ancillary materials	(kg/m^3)	(lb/MBF[1])	Database
Hydraulic fluid	2.41E-01	9.16E-01	US-EI
Motor oil	6.63E-02	2.52E-01	US-EI
Grease	0.00E+00	0.00E+00	US-EI
Cardboard	1.21E-04	4.61E-04	US-EI
Plastic strapping	6.36E-02	2.42E-01	US LCI
Paint	2.12E-03	8.06E-03	US-EI
Potable water	1.81E+00	6.90E+00	US-EI
Replacement sticker	3.40E+00	1.30E+01	US LCI

[1] MBF = thousand board feet.

5 Data Quality Summary

Data quality summary is listed in Table 5 1. Data quality relates to the actual scenario being studied. Therefore, primary data collected from industry ranks the highest with peer-reviewed studies ranking in the middle. In addition, data within LCI databases are typically peer-reviewed before being entered into the databases so is ranked as medium-high as the data were peer-reviewed twice.

Table 5-1: Data quality summary for cradle-to-gate data

Decking	Data source	Data quality	Comments
WPC	Secondary (various sources)	Medium	From peer-reviewed study by Mahalle and O'Connor (2009) and industry sources listed in References
Redwood	Primary data (surveys)	High	100% allocated to decking
PVC	Secondary (various sources)	Medium	From peer-reviewed study by Mahalle and O'Connor (2009) and industry sources listed in References
Energy/Ancillary materials	Tertiary data (US LCI and US Ecoinvent Databases)	Medium-high	

6 Installation and Use Phase Life-Cycle Inventories

This section covered the ancillary material requirements and processes involved in the installation, use, and maintenance of decking products throughout their service lives. The use of phase inventories accounted for all the material and energy inputs and processes associated with the final products leaving the mill gate and the installation, use, and maintenance. Since redwood decking is primarily used along the Pacific Coast, product transportation was modeled for two building site locations. One represented local markets in San Francisco, CA, and the second represented a more distant market in Seattle, WA.

Installation specifications for all of the decking materials evaluated are shown in **Table 6-1**. It is assumed that a residential light-duty deck was installed according to the TimberTech, Trex, and CRA installation guidelines. As per these specifications, WPC, and PVC decking have the same joist spans and fastener specifications. The only major difference is the 24-inch joist space for the redwood deck versus 16 inches for the other decks. The joist spacing is increased because the redwood decking boards are thicker than the other products and have a higher strength that allows for wider joist spacing. Therefore, less structural lumber for the deck joists is required for the redwood deck per functional unit.

Table 6-1: Installation guidelines for the various decking materials

Decking material	Size of board (mm)	Joist span (mm)	Fasteners	Gaps between boards and solid objects (e.g., wall)
WPC[1]	31 × 140 (1.25 × 6 in)	400 (16 in)	62.5-mm (2.5 in-) galvanized screws (no. 8 or 10)	Width-to-width – 6.25 mm (0.25 in) End-to-end – 3.125 mm (0.125 in) Abutting solid objects – 6.25 mm (0.25 in)
Redwood[2]	38 × 140 (2 × 6 in)	600 (24 in)	Same as WPC	Width-to-width – 4.69 mm (0.188 in) End-to-end – flush Abutting solid objects – flush
PVC[3]	25 × 140 (1 × 6 in)	400 (16 in)	Same as WPC	Width-to-width – 6.25 mm (0.25 in) End-to-end – 4.69 mm (0.188 in) Abutting solid objects – 6.25 mm (0.25 in)

[1] Mahalle and O'Connor (2009) p. 37.
[2] Personal communication 09/30/2011, Charlie Jourdain, President, California Redwood Association (CRA).
[3] Personal communication 01/18/2012, Charlie Jourdain, President, CRA.

The decking installation and use phase LCI included the transportation of the decking from the production facility to the warehouses and then to the selected building sites. Also, the materials and energy used in the installation, use, and maintenance of the deck was considered. Energy used by the nail guns and drills during installation was assumed to be minor and was not included in the LCI. All decking materials were assumed to have similar cleaning guidelines. For example, washing the deck surface with a detergent and bleach to kill mold and mildew is suggested annually for all decking materials (Mahalle and O'Connor 2009; Trex 2013; TimberTech 2013). In addition, to maintain decking throughout its service life regardless of the decking material, the deck should have dirt and debris removed on a semiannual basis.

Based on the information considered, decking maintenance and installation procedures were similar enough between the different decking materials to disregard in performing the full LCA. Additionally, product transportation will likely substantially outweigh all other impacts for this stage. Other material attributes related to this life-cycle stage are shown below.

6.1 Polyvinyl Chloride

6.1.1 *Transport*

PVC decking boards were made in a production facility located in Columbus, OH (TimberTech 2013; EBN 2012). Diesel trains (80%) and diesel tractor-trailer (20%) were assumed to transport the PVC decking to distribution centers in San Francisco (3,800 km) and Seattle (3,800 km). Upon arrival at the distribution centers, single-unit trucks were assumed to transport the WPC deck boards an average of 20 km to the building sites for installation.

6.1.2 *Use Phase Inputs*

A 100 ft^2- (9.29 m^2-) PVC deck requires 211 lineal feet (64.3 m) of 4/4- (25 mm-) deck boards. In addition, a 2.3% material loss was assumed during installation (from trimming) and the waste material sent to a landfill for disposal. Like other large PVC decking manufacturers, TimberTech offers a limited lifetime warranty on their decking products. Therefore, in this study, a PVC deck had an expected service life of 25 years with proper care and maintenance.

6.2 Wood–Plastic Composite (virgin and recycled)

6.2.1 *Transport*

WPC decking boards were made in a production facility located in Fernley, NV (Trex 2012). Diesel tractor-trailers were assumed to transport the decking to distribution centers located in San Francisco (400 km) and Seattle (1,200 km). Upon arrival at the distribution centers, single-unit trucks were assumed to transport the WPC deck boards an average of 20 km to building sites for installation.

6.2.2 *Use Phase Inputs*

A 100 ft^2- (9.29 m^2-) WPC deck requires 211 lineal feet (64.3 m) of 5/4 (31 mm) deck boards. In addition, a 2.3% material loss was assumed during installation (from trimming) and the waste material sent to a landfill for disposal. Like other large WPC decking manufacturers, Trex offers a 25-year warranty on their decking products. Therefore, in this study, a WPC deck had an expected service life of 25 years with proper care and maintenance.

6.3 Redwood

6.3.1 *Transport*

Redwood decking was primarily used within the region of manufacture (U.S. West Coast), unlike other decking materials. Therefore, the lower product transport distance resulted in a lower impact for this stage of the life-cycle analysis. From the survey data, weight-averaged product transportation distances were calculated for the green and dry redwood decking products. However, to facilitate the product comparison with other decking materials regarding San Francisco and Seattle, several assumptions were necessary.

For example, San Francisco lies on the southern end of the redwood timber range with the majority of redwood decking production occurring roughly 250 to 600 km away. Therefore, it was assumed that diesel tractor-trailers transported the redwood decking approximately 300 km to a distribution center. In the case of Seattle, diesel tractor-trailers were assumed to transport the redwood decking approximately 1,000 km to the distribution centers. The weight of the water found within the decking added additional burdens. Assuming green decking (34.6% of total volume) at 127% MC and dry decking (65.4% of total volume) at 19% MC, a weighted-average value of 56.4% MC was estimated and used in estimating the additional environmental impacts during decking transportation. Upon arrival at the distribution centers, diesel single-unit trucks were used to transport the redwood deck boards an average of 20 km to the building sites for installation.

6.3.2 *Use Phase Inputs*

A residential 100 ft^2- (9.29 m^2-) redwood deck requires 211 lineal feet (64.3 m) of nominal 2 × 6 (38- × 140-mm) deck boards. In addition, because of redwood's natural durability, no stains or preservatives were applied to the installed deck boards[11]. Therefore, it was assumed that redwood deck boards were not stained and that they would develop a natural weathered appearance within several months. A 3% material loss was assumed during installation (from trimming) and the

[11] Personal communication 01/18/2012, Charlie Jourdain, President, California Redwood Association.

waste material was sent to a landfill for disposal (Mahalle and O'Connor 2009). With proper maintenance, redwood decking should last 25 years before decking boards would need to be replaced.

7 End of life Phase

Final disposition of old deck boards had a substantial influence on the environmental impacts and the LCA, depending on the type of material from which the decking was manufactured. Prior to the introduction of WPC decking materials, wood decking was simply disposed of in a landfill and considered inert without any environmental impact once the material was in the landfill. Therefore, only transportation to the landfill and the energy to landfill the material needed to be considered.

In contrast, the present study assumed that, while the decking was disposed of in a landfill, the wood decking partially decomposed. Research has shown that a portion of the discarded wood decking (about 23%) breaks down anaerobically when stored in a landfill (Skog 2008). The wood decomposes into biogenic methane and biogenic carbon dioxide on a 50:50 molar ratio. As the biogenic methane, a potent greenhouse gas (GHG), rises to the surface of the landfill, 10% of the biogenic methane oxidizes into biogenic CO_2. Therefore, the CH_4:CO_2 molar ratio at the landfill surface is 45:55.

To help mitigate climate change, it is desirable that biogenic methane, which is a much more potent GHG than CO_2, be captured and burned (i.e., flared). Additionally, energy may be recovered and is an added benefit as the landfill gas captured and burned avoids the production of natural gas for energy. EPA (2011) and Salazar and Meil (2009) provided the background calculations found in **Appendix 16– Landfill Equations**. **Table 7-1** shows the GHG emission profile for the baseline scenario, a landfill with energy recovery.

Table 7-1: GHG emissions from wood landfilled with standard methane capture

GHG Emissions	kg GHG per OD kg wood	kg GHG per 100 ft^2 (redwood)[1]
Methane, biogenic[2]	0.0180	2.43
Carbon dioxide, biogenic[2]	0.0605	8.17
Carbon dioxide, biogenic[3]	0.231	31.2
Carbon dioxide, biogenic[4]	0.0990	13.4

[1] 135 oven-dried kg redwood per 100 ft^2.
[2] Released directly into air.
[3] Released after energy recovery (70%).
[4] Release after flaring (30%) – energy not recovered.

Landfill gas (LFG) contains a considerable percentage of biogenic methane. Biogenic and fossil methane are the same chemically. Fossil methane is the primary component of natural gas. Therefore, LFG capture for energy production would offset some natural gas production. In this study, the avoided natural gas production due to the capture of LFG was estimated to be 0.054 kg (0.0753 m^3) of natural gas production per OD kg of wood decomposing in the landfill, assuming a 23% decomposition rate and a 75% landfill methane capture of 0.1004 m^3 /OD kg at landfill surface (Salazar and Meil 2009). The remaining 25% of biogenic methane (0.018 kg/OD kg wood) was emitted directly into the atmosphere. So for the functional unit of 100 ft^2 of decking area (135 OD kg) of redwood decking sent to a landfill with methane capture, a total of 7.31 kg (10.2 m^3) of natural gas production was avoided. To model the impact on redwood decking, cradle-to-gate production of natural gas at the plant was entered as an avoided product to account for the environmental impacts not occurring by using LFG instead.

All decking was assumed to be removed manually during the deconstruction of the deck. Therefore, the impact of removal was not included in the LCA. Both PVC and WPC decking products have no other impacts except transportation to the inert landfill and handling at landfill.

8 Life-Cycle Impact Assessment

This section of the report covers the impact assessment of the life-cycle assessment. The LCI flows from the various decking materials provided the basis for the LCIA. The TRACI 2.1 Method data incorporated into SimaPro provided the framework for calculating the environmental mid-point categories listed in Section 3-6. The GWP profiles presented included the carbon stored in the redwood and WPC decking products. The LCIA provided input for builders, architects, engineers, and designers on the various attributes of raw materials, product choices, and disposal methods. Learning the LCIA of a particular material allows stakeholders to make informed product choices based on science rather than anecdotal evidence, assuming that the LCIA analysis was transparent.

The LCIA data provided in this report for the individual decking materials assumed that half the decks were built in San Francisco, CA, and the other half in Seattle, WA, the two most popular destinations for redwood decking. Redwood decking is generally used where it is manufactured, which lowers its product transportation distance.
The first section showed the LCIAs for individual decking materials by the following stages: 1) cradle-to-gate manufacturing, 2) product transportation from production facility to customer, 3) use phase, and 4) removal of decking and disposal in a MSW landfill with methane capture.

The second section provided overall decking numbers. The second section showed overall decking numbers assuming that half the decks were constructed in San Francisco and the other half in Seattle, WA. In addition, a sensitivity analysis was performed using mass allocation instead of the no allocation approach and the LCA results are shown in Section 9. Section 10 highlighted the required cradle-to-gate LCA data for developing a business-to-business (B2B) EPD. Furthermore, a scenario analysis was completed using EOL values based on EPA (2006) and used in Mahalle and O'Connor (2009) study on western redcedar.

8.1 PVC Decking

This study modeled the entire life cycle of PVC decking. PVC decking production required raw materials and generated emissions. SimaPro modeled the inputs provided in Section 4.1.

Table 8-1 shows the impacts associated with building a 100 ft^2- (9.29 m^2-) deck. **Table 8-2** indicates the same impacts converted to a cubic meter basis. These tables indicate that the greatest impacts occurred during the cradle-to-gate manufacturing process. Cumulated unallocated total energy consumption was 10,600 MJ/100 ft^2 (42,500 MJ/m^3) with about 93% (9,840/10,060) of the energy use associated with the cradle-to-gate manufacturing process. This result was consistent with the GWP as the cradle-to-gate manufacturing process generated 86% (368/426) of the total. The in-service use phase had a minimal impact on the LCA because the only inputs were derived from cleaning the deck semiannually. Biomass energy of 6.4 MJ/100 ft^2 (27 MJ/m^3) was attributable to grid electricity, less than 1% of total.

Table 8-1: Life-cycle impact assessment for 100 ft^2 (9.29 m^2) of polyvinyl chloride decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	368	57.8	0.029	1	426
Ozone depletion	kg CFC-11 eq	1.60E-05	2.25E-08	1.98E-09	3.66E-11	1.60E-05
Smog	kg O_3 eq	20.5	9.4	0.001	0.18	30.0
Acidification	kg SO_2 eq	4.32	0.29	0.00	0.01	4.61
Eutrophication	kg N eq	0.088	0.020	0.000	0.000	0.108
Respiratory effects	kg PM2.5 eq	0.270	0.006	0.000	0.000	0.276
Primary energy consumption	Unit					
Non-renewable fossil	MJ	9378	783	1	7	10200
Non-renewable nuclear	MJ	442	7	0	0	449
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	1	0	0	15
Renewable, biomass	MJ	6	0	0	0	6
Total primary energy	MJ	9840	791	1	7	10600
Material resources consumption[1]	Unit					
Non-renewable materials	kg	157	0	0	0	157
Renewable materials	kg	0	0	0	0	0
Fresh water	L	4410	2	88	0	4500
Waste generated	Unit					
Solid waste	kg	0.736	0.000	0.000	0.000	0.736

[1] Non-fuel resources.

Table 8-2: Life-cycle impact assessment for 1 m^3 of polyvinyl chloride decking

Impact Category	Unit	Cradle-to-Gate	Transportation to Customer	Use Phase	Landfill	Total
Global warming	kg CO_2 eq	1560	245	0	2	1810
Ozone depletion	kg CFC-11 eq	6.79E-05	2.25E-08	1.98E-09	3.66E-11	6.79E-05
Smog	kg O_3 eq	86.7	39.9	0.0	0.8	127
Acidification	kg SO_2 eq	18.3	1.2	0.0	0.0	19.6
Eutrophication	kg N eq	0.371	0.084	0.001	0.001	0.457
Respiratory effects	kg PM2.5 eq	1.144	0.026	0.000	0.000	1.17
Primary Energy Consumption	Unit					
Non-renewable fossil	MJ	39700	3320	2	30	43100
Non-renewable nuclear	MJ	1872	28	0	0	1900
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	62	3	0	0	65
Renewable, biomass	MJ	27	0	0	0	27
Total primary energy	MJ	41700	3350	3	30	45000
Material resources consumption[1]						
Non-renewable materials	kg	663	0	0	0	663
Renewable materials	kg	0	0	0	0	0
Fresh water	L	18700	9	370	0	19100
Waste generated	Unit					
Solid waste	kg	3.12	0.00	0.00	0.00	3.12

[1] Non-fuel resources.

Table 8-3 and **Table 8-4** show the environmental performance of 100 ft^2 (9.29 m^2) and 1 m^3 of PVC decking from cradle-to-gate, respectively. The categories of material extraction and product production combine to form the cradle-to-gate LCIA shown in **Tables 8-1** and **8-2**. Additional information includes non-renewable and renewable materials that fall under the category "Material resources consumption (Non-fuel resources)".

Table 8-3: Environmental performance of 100 ft^2 (9.29 m^2) of polyvinyl chloride decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Material extraction	Product production
Global warming	kg CO_2 eq	368	0	285	83
Ozone depletion	kg CFC-11 eq	1.60E-05		1.39E-05	2.12E-06
Smog	kg O_3 eq	20.5		14.91	5.54
Acidification	kg SO_2 eq	4.32		3.64	0.682
Eutrophication	kg N eq	0.088		0.072	0.015
Primary energy consumption	Unit				
Non-renewable fossil	MJ	9378		8249	1129
Non-renewable nuclear	MJ	442		276	166
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	14.6		12.4	2.3
Renewable, biomass	MJ	6.26		3.04	3.21
Total primary energy	MJ	9840		8540	1300
Material resources consumption[1]	Unit				
Non-renewable materials	kg	157		0	157
Renewable materials	kg	0		0	0
Fresh water	L	4410		1180	3230
Waste generated	Unit				
Solid waste	kg	0.736		0.148	0.589

[1] Non-fuel resources.

Table 8-4: Environmental performance of 1 m^3 of polyvinyl chloride decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Material extraction	Product production
Global warming	kg CO_2 eq	1560	0	1207	353
Ozone depletion	kg CFC-11 eq	6.79E-05		5.89E-05	8.99E-06
Smog	kg O_3 eq	86.7		63.2	23.5
Acidification	kg SO_2 eq	18.3		15.4	2.9
Eutrophication	kg N eq	0.371		0.307	0.064
Primary energy consumption	Unit				
Non-renewable fossil	MJ	39737		34953	4784
Non-renewable nuclear	MJ	1872		1170	703
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	62		52	10
Renewable, biomass	MJ	27		13	14
Total primary energy	MJ	41700		36200	5510
Material resources consumption[1]	Unit				
Non-renewable materials	kg	663		0	633
Renewable materials	kg	0		0	0
Fresh water	L	18700		5000	13700
Waste generated	Unit				
Solid waste	kg	3.12		0.625	2.495

[1] Non-fuel resources.

8.2 WPC Decking

This study modeled the entire life cycle of virgin and recycled WPC decking. The manufacturing process requires raw materials and generates emissions. SimaPro modeled the variable inputs specified in Section 4.2. Dry planer shavings left the softwood mill with no environmental burdens because softwood lumber was the primary product and to be consistent with treatment of other wood residues in previous decking studies.

8.2.1 *Virgin Wood–plastic Composite Decking*

Table 8-5 shows the impacts generated for a 100 ft^2- (9.29 m^2-) area of deck, whereas **Table 8-6** indicates the impacts converted to a cubic meter basis. The data presented in these tables demonstrate that the greatest impacts occurred during the cradle-to-gate manufacturing process. The cumulated unallocated total energy consumption was 14,700 MJ/100 ft^2 (53,000 MJ/m^3) of deck with about 98% (14,400/14,700) of energy use associated with the cradle-to-gate manufacturing process. Carbon stored in the final product was 244 kg CO_2/100 ft^2 (881 kg CO_2-eq/m^3)[12]. This result was consistent with the GWP as the cradle-to-gate manufacturing process generated about 96% (486/508) of the total prior minus the carbon stored in the final product[13]. Including carbon storage lowered total GWP from 508 to 264 kg CO_2-eq/100 ft^2 (950 kg CO_2-eq/m^3), a reduction of 244 kg CO_2-eq/100 ft^2 (881 kg CO_2-eq/m^3). The use phase had minimal impact on the LCIA because the only inputs in this phase came from cleaning the deck semiannually.

An interesting outcome of manufacturing the WPC decking in Nevada versus the East Coast was the large drop in fossil energy (i.e., diesel) use required. The main reason was that virgin WPC decking manufacturing occurred in Fernley, NV, versus previous studies with WPC decking manufacturing in the East. Therefore, significantly less product transportation occurred to provide virgin WPC decking to the west coast market.

Softwood sawmills use biomass energy to kiln-dry lumber before planing (Puettmann et al. 2010). However, biomass energy shown of 9.0 MJ/100 ft^3 (32 MJ/m^3) was attributable to the electric grid not to the wood portion of the WPC decking, the same as PVC decking. Planer shavings are the result of planing softwood lumber that is typically kilned dry (Puettmann et al. 2010). However, in the present study, planer shavings produced at the softwood sawmill had no environmental burdens assign to them but do carry the inherent carbon found in all wood products.

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[12] 267 kg per functional unit × 50% wood × 50% carbon × 44/12 = 244 kg CO_2-eq.
[13] 244+242=486; 244+264=508.

Table 8-5: Life-cycle impact assessment for 100 ft² (9.29 m²) of virgin wood–plastic composite decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	242	20.8	0.029	1	264
Ozone depletion	kg CFC-11 eq	1.36E-05	7.97E-10	1.98E-09	6.24E-11	1.37E-05
Smog	kg O_3 eq	32.6	3.4	0.001	0.31	36.3
Acidification	kg SO_2 eq	5.83	0.10	0.00	0.01	5.94
Eutrophication	kg N eq	0.229	0.007	0.000	0.001	0.237
Respiratory effects	kg PM2.5 eq	0.336	0.002	0.000	0.000	0.338
Primary energy consumption	Unit					
Non-renewable fossil	MJ	13540	271	1	12	13800
Non-renewable nuclear	MJ	236	2	0	0	238
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	614	0	0	0	614
Renewable, biomass	MJ	9	0	0	0	9
Total primary energy	MJ	14400	273	1	12	14700
Material resources consumption[1]	Unit					
Non-renewable materials	kg	134	0	0	0	134
Renewable materials	kg	133	0	0	0	0
Fresh water	L	3270	0	88	0	3360
Waste generated						
Solid waste	kg	0.070	0.000	0.000	0.000	0.070

[1] Non-fuel resources.

Table 8-6: Life-cycle impact assessment for one m³ of virgin wood–plastic composite decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	875	75	0	3	953
Ozone depletion	kg CFC-11 eq	4.93E-05	2.25E-08	1.98E-09	3.66E-11	4.93E-05
Smog	kg O_3 eq	117.7	12.2	0.0	1.1	131
Acidification	kg SO_2 eq	21.0	0.4	0.0	0.0	21.5
Eutrophication	kg N eq	0.828	0.025	0.001	0.002	0.856
Respiratory effects	kg PM2.5 eq	1.212	0.008	0.000	0.001	1.22
Primary energy consumption	Unit					
Non-renewable fossil	MJ	48900	980	2	44	50000
Non-renewable nuclear	MJ	851	9	0	0	860
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2218	0	0	0	2218
Renewable, biomass	MJ	32	0	0	0	32
Total primary energy	MJ	52000	990	2	44	53100
Material resources consumption[1]	Unit					
Non-renewable materials	kg	482	0	0	0	482
Renewable materials	kg	480	0	0	0	480
Fresh water	L	11800	0	319	0	12100
Waste generated	Unit					
Solid waste	kg	0.251	0.000	0.000	0.000	0.251

[1] Non-fuel resources.

Table 8-7 and **Table 8-8** show the environmental performance of 100 ft² (9.29 m²) and 1 m³ of virgin WPC decking from cradle-to-gate, respectively. The categories of forest carbon uptake, material extraction, and product production combine to form the cradle-to-gate LCIA shown in **Tables 8-5** and **8-6**. Additional information includes non-renewable and renewable materials that fall under the category “Material resources consumption (Non-fuel resources)”.

Table 8-7: Environmental performance of 100 ft^2 (9.29 m^2) of virgin wood–plastic composite decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Material extraction	Product production
Global warming	kg CO_2 eq	242	–244	272	215
Ozone depletion	kg CFC-11 eq	1.36E-05		1.27E-05	9.15E-07
Smog	kg O_3 eq	32.6		18.95	13.66
Acidification	kg SO_2 eq	5.83		4.02	1.806
Eutrophication	kg N eq	0.229		0.203	0.027
Primary energy consumption	Unit				
Non-renewable fossil	MJ	13540		10552	2988
Non-renewable nuclear	MJ	236		100	135
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	614		18.7	595.7
Renewable, biomass	MJ	8.9		5.9	3
Total primary energy	MJ	14400		10700	3720
Material resources consumption[1]	Unit				
Non-renewable materials	kg	134		0	134
Renewable materials	kg	133		0	133
Fresh water	L	3270		2522	744
Waste generated	Unit				
Solid waste	kg	0.070		0.070	0.000

[1] Non-fuel resources.

Table 8-8: Environmental performance of 1 m^3 of virgin wood–plastic composite decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Material extraction	Product production
Global warming	kg CO_2 eq	874	–881	980	775
Ozone depletion	kg CFC-11 eq	4.93E-05		4.60E-05	3.30E-06
Smog	kg O_3 eq	117.7		68.4	49.3
Acidification	kg SO_2 eq	21.0		14.5	6.5
Eutrophication	kg N eq	0.828		0.732	0.097
Primary energy consumption	Unit				
Non-renewable fossil	MJ	48879		38094	10786
Non-renewable nuclear	MJ	851		362	489
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2218		67	2150
Renewable, biomass	MJ	32		21	11
Total primary energy	MJ	52000		38600	13400
Material resources consumption[1]	Unit				
Non-renewable materials	Kg	482		0	482
Renewable materials	Kg	480		0	480
Fresh water	L	11800		9110	2690
Waste generated	Unit				
Solid waste	Kg	0.251		0.251	0.000

[1] Non-fuel resources.

8.2.2 *Recycled WPC Decking*

SimaPro was used to model the variable inputs listed in section 4.2. **Table 8-9** shows the impacts generated from building 100 ft^2 (9.29 m^2) of decking from recycled WPC while **Table 8-10** demonstrates the impacts converted to a cubic meter basis. The tables show that the greatest impacts occurred during the cradle-to-gate manufacturing process. The cumulated unallocated total energy consumption was 6,690 MJ/100 ft^2 (24,000 MJ/m^3) with about 96% (6390/6690) of the energy use being attributed with the cradle-to-gate manufacturing process. Carbon stored in the final product was the same as virgin WPC decking at 244 kg CO_2/100 ft^2 (964 kg CO_2-eq/m^3). This result was consistent with the GWP as the cradle-to-gate manufacturing process generated about 94% (366/388) of the total outputs minus the carbon stored in the final product[14]. Including carbon storage lowered total GWP from 388 to 144 kg CO_2-eq/100 ft^2 (510 kg CO_2-eq/m^3), a reduction of 244 kg CO_2-eq/100 ft^2 (881 kg CO_2-eq/m^3). The cumulative allocated energy was about 54%[15] lower than for the virgin WPC decking. The use phase had a minimal impact on the LCIA because the only inputs in this phase came from cleaning the deck semiannually. An in the previous case, manufacturing the recycled WPC decking in Nevada versus the East coast resulted in a large drop in the fossil energy use required to transport the decking material to the west coast.

Table 8-9: Life-cycle impact assessment for 100 ft^2 (9.29 m^2) of recycled wood–plastic composite decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	122	20.8	0.029	1	144
Ozone depletion	kg CFC-11 eq	1.16E-05	7.97E-10	1.98E-09	6.24E-11	1.16E-05
Smog	kg O_3 eq	24.8	3.4	0.001	0.31	28.5
Acidification	kg SO_2 eq	2.75	0.10	0.00	0.01	2.86
Eutrophication	kg N eq	0.196	0.007	0.000	0.001	0.203
Respiratory effects	kg PM2.5 eq	0.154	0.002	0.000	0.000	0.157
Primary energy consumption	Unit					
Non-renewable fossil	MJ	5530	271	1	12	5820
Non-renewable nuclear	MJ	166	2	0	0	168
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	693	0	0	0	693
Renewable, biomass	MJ	9	0	0	0	9
Total primary energy	MJ	6400	273	1	12	6690
Material resources consumption[1]						
Non-renewable materials	kg	134	0	0	0	134
Renewable materials	kg	133	0	0	0	133
Fresh water	L	3350	0	88	0	3440
Waste generated	Unit					
Solid waste	kg	8.60	0.00	0.00	0.00	8.60

[1]Non-fuel resources.

[14] 122+244 = 366; 144+244 = 388.

[15] $54\% = \frac{(14{,}700-6{,}690)}{14{,}700}$.

Table 8-10: Life-cycle impact assessment for one m^3 of recycled wood–plastic composite decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	441	75	0	3	519
Ozone depletion	kg CFC-11 eq	4.18E-05	2.25E-08	1.98E-09	3.66E-11	4.18E-05
Smog	kg O_3 eq	89.4	12.2	0.0	1.1	103
Acidification	kg SO_2 eq	9.9	0.4	0.0	0.0	10.3
Eutrophication	kg N eq	0.706	0.025	0.001	0.002	0.734
Respiratory effects	kg PM2.5 eq	0.557	0.008	0.000	0.001	0.57
Primary energy consumption	Unit					
Non-renewable fossil	MJ	20000	980	2	44	21100
Non-renewable nuclear	MJ	598	9	0	0	610
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2502	0	0	0	2502
Renewable, biomass	MJ	33	0	0	0	33
Total primary energy	MJ	23100	990	2	44	24200
Material resources consumption[1]	Unit					
Non-renewable materials	kg	482	0	0	0	482
Renewable materials	kg	480	0	0	0	480
Fresh water	L	12100	0	320	0	12400
Waste generated	Unit	441	75	0	3	519
Solid waste	Kg	4.18E-05	2.25E-08	1.98E-09	3.66E-11	4.18E-05

[1] Non-fuel resources.

Table 8-15 and **Table 8-16** show the environmental performance of 100 ft^2 (9.29 m^2) and 1 m^3 of recycled WPC decking from cradle-to-gate, respectively. The categories of forest carbon uptake, material extraction, and product production combine to form the cradle-to-gate LCIA shown in **Tables 8-9** and **8-10**. Additional information includes non-renewable and renewable materials that fall under the category "Material resources consumption (Non-fuel resources)".

Table 8-11: Environmental performance of 100 ft² (9.29 m²) of recycled wood–plastic composite decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	122	–244	151	215
Ozone depletion	kg CFC-11 eq	1.16E-05		1.07E-05	9.15E-07
Smog	kg O_3 eq	24.8		11.12	13.66
Acidification	kg SO_2 eq	2.75		0.95	1.805
Eutrophication	kg N eq	0.196		0.169	0.027
Primary energy consumption	Unit				
Non-renewable fossil	MJ	5527		2540	2987
Non-renewable nuclear	MJ	166		30	135
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	693		98	596
Renewable, biomass	MJ	9		6	3
Total primary energy	MJ	6390		2670	3720
Material resources consumption[1]	Unit				
Non-renewable materials	kg	134		0	134
Renewable materials	kg	133		0	133
Fresh water	L	3340		2600	740
Waste generated	Unit				
Solid waste	kg	8.60		8.60	0.00

[1] Non-fuel resources.

Table 8-12: Environmental performance of 1 m³ of recycled wood–plastic composite decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	441	–881	547	775
Ozone depletion	kg CFC-11 eq	4.18E-05		3.85E-05	3.30E-06
Smog	kg O_3 eq	89.4		40.1	49.3
Acidification	kg SO_2 eq	9.9		3.4	6.5
Eutrophication	kg N eq	0.706		0.610	0.097
Primary energy consumption	Unit				
Non-renewable fossil	MJ	19953		9169	10784
Non-renewable nuclear	MJ	598		109	489
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	2502		352	2150
Renewable, biomass	MJ	33		23	11
Total primary energy	MJ	23100		9640	13430
Material resources consumption[1]	Unit				
Non-renewable materials	kg	482		0	482
Renewable materials	kg	480		0	480
Fresh water	L	12100		9390	2670
Waste generated	Unit				
Solid waste	kg	31.0		31.0	0.0

[1] Non-fuel resources.

8.3 Redwood Decking

To be consistent with the new North American wood PCR introduced in 2011, the LCIA did not include biogenic CO_2 emissions and forest carbon uptake but did include carbon stored in the final product (FPInnovations 2011). For consistency, WPC decking products that stored carbon were analyzed and reported in this study in the same manner. This section does not cover the specifications outlined in the North American Structural and Architectural Wood Products PCR. However, Section 10 did cover the necessary cradle-to-gate LCIA data specifications.

The SimaPro 7.3 program was used to model the input variables listed in Section 4.3 considering the above changes shows the impacts associated with building a 100-ft^2 (9.29-m^2) deck, whereas **Table 8-14** displays the impacts generated on a cubic meter basis. The tables show that the greatest environmental impacts occurred during the cradle-to-gate manufacturing process that included redwood resource harvesting and product production. The cumulated unallocated total energy consumption was 447 MJ/100 ft^2 (1,270 MJ per m^3) of deck with most of energy use associated with the cradle-to-gate manufacturing process. This indicates that the other cradle-to-gate LCI stages for both PVC and WPC decking products have a greater impact on energy use. During final disposition, the biogenic methane captured avoids natural gas production and the resultant reduction of 424 MJ/100 ft^2 of energy was substantial. The biomass energy contributes 94 MJ/100 ft^2 of deck to the total energy balance.

The low biomass energy associated with redwood decking was again counterintuitive in comparison to other wood products. The reason for this result was that minimal kiln-drying occurred during redwood decking manufacturing. Air-drying was the primary source of removing water from the redwood decking. Kiln–drying is the most energy-intensive unit process for producing lumber-type products (Simpson 1991; Bergman and Bowe 2008; Puettmann et al. 2010; Bergman and Bowe 2012). Additionally, redwood decking was kiln-dried after air-drying to less than 30% MC on the air yard. Biomass energy represents about 21% (94/447) of total energy used and the GWP value was negative, –163 kg CO_2-eq/100 ft^2 (–460 kg CO_2-eq/m^3) because redwood decking stores the carbon sequestered by trees. Redwood decking stores carbon equivalent to 262 kg CO_2/100 ft^2 (738 kg CO_2/m^3) while in-service. Therefore, when not considering carbon storage in the redwood decking while in-service, 98 kg CO_2-eq/100 ft^2 (278 kg CO_2-eq/m^3) of redwood decking was emitted over the full life cycle. This value includes the biogenic methane not captured from the landfills and subsequently emitted to the atmosphere (2.5 kg/100 ft^2). As with all of the decking products considered, the use phase had a minimal impact on the LCIA because the only inputs come from cleaning the deck semiannually.

Table 8-13: Life-cycle impact assessment for 100 ft^2 (9.29 m^2) of redwood decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	–229	14.6	0.029	52	-163
Ozone depletion	kg CFC-11 eq	1.35E-06	5.57E-10	1.99E-09	3.62E-10	1.36E-06
Smog	kg O_3 eq	6.8	2.4	0.001	0.26	9.5
Acidification	kg SO_2 eq	0.33	0.07	0.00	-0.19	0.21
Eutrophication	kg N eq	1.71E-02	4.87E-03	1.97E-04	–6.12E-04	2.16E-02
Respiratory effects	kg PM2.5 eq	1.62E-02	1.53E-03	1.31E-05	–1.20E-02	5.74E-03
Primary energy consumption	Unit					
Non-renewable fossil	MJ	504	198	1	–423	280
Non-renewable nuclear	MJ	38	2	0	–1	39
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	34	0	0	0	34
Renewable, biomass	MJ	94	0	0	0	94
Total primary energy	MJ	670	200	1	–424	447
Material resources consumption[1]	Unit					
Non-renewable materials	Kg	0.8	0	0	0	0.8
Renewable materials	Kg	136	0	0	0	136
Fresh water	L	140	0	89	0	229
Waste generated	Unit					
Solid waste	kg	0.223	0.000	0.000	0.000	0.223

[1] Non-fuel resources.

Table 8-14: Life-cycle impact assessment for one m^3 of redwood decking

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	–648	41	0.08	147	–460
Ozone depletion	kg CFC-11 eq	3.82E-06	1.57E-09	5.63E-09	1.02E-09	3.83E-06
Smog	kg O_3 eq	19.3	6.8	0.0	0.7	26.8
Acidification	kg SO_2 eq	0.92	0.21	0.00	–0.54	0.59
Eutrophication	kg N eq	4.83E-02	1.38E-02	5.58E-04	–1.73E-03	6.09E-02
Respiratory effects	kg PM2.5 eq	4.58E-02	4.31E-03	3.69E-05	–3.39E-02	1.62E-02
Primary energy consumption	Unit					
Non-renewable fossil	MJ	1424	559	2	–1195	780
Non-renewable nuclear	MJ	107	5	0	–3	109
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	96	0	0	0	98
Renewable, biomass	MJ	265	0	0	0	265
Total primary energy	MJ	1892	564	2	–1197	1270
Material resources consumption[1]						
Non-renewable materials	kg	2	0	0	0	2
Renewable materials	kg	383	0	0	0	383
Fresh water	L	395	0	251	0	646
Waste generated	Unit					
Solid waste	kg	0.629	0.000	0.000	0.000	0.629

[1] Non-fuel resources.

Table 8-15 and **Table 8-16** show the environmental performance of 100 ft^2 (9.29 m^2) and 1 m^3 of redwood decking from cradle-to-gate, respectively. The categories of forest carbon uptake, material extraction, and product production combine to form the cradle-to-grave LCIA shown in **Tables 8-13 and 8-14**. Additional information includes non-renewable and renewable materials that fall under the category "Material resources consumption (Non-fuel resources)".

Table 8-15: Environmental performance of 100 ft^2 (9.29 m^2) of redwood decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	–229	–262	14.3	17.8
Ozone depletion	kg CFC-11 eq	1.35E-06		2.46E-08	1.33E-06
Smog	kg O_3 eq	6.84		5.32	1.52
Acidification	kg SO_2 eq	0.326		0.158	0.168
Eutrophication	kg N eq	1.71E-02		1.03E-02	6.80E-03
Primary energy consumption	Unit				
Non-renewable fossil	MJ	504		208	296
Non-renewable nuclear	MJ	38		2.1	35.8
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	34		0.52	33.5
Renewable, biomass	MJ	94		0.00	93.8
Total primary energy	MJ	670		211	459
Material resources consumption[1]	Unit				
Non-renewable materials	kg	0.77		0	0.77
Renewable materials	kg	136		0	136
Fresh water	L	140		27	113
Waste generated	Unit				
Solid waste	kg	0.223		0.00	0.223

[1] Non-fuel resources.

Table 8-16: Environmental performance of 1 m^3 of redwood decking from cradle-to-gate

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	–648	–738	40.3	49.2
Ozone depletion	kg CFC-11 eq	3.82E-06		6.938E-08	3.754E-06
Smog	kg O_3 eq	19.3		15.0	4.3
Acidification	kg SO_2 eq	0.920		0.447	0.474
Eutrophication	kg N eq	4.83E-02		2.912E-02	1.921E-02
Primary energy consumption	Unit				
Non-renewable fossil	MJ	1424		589	835
Non-renewable nuclear	MJ	107		6	101
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	96		1	95
Renewable, biomass	MJ	265		0	265
Total primary energy	MJ	1892		596	1296
Material resources consumption[1]	Unit				
Non-renewable materials	kg	2.18		0	2.18
Renewable materials	kg	383		0	383
Fresh water	L	395		77	318
Waste generated	Unit				
Solid waste	kg	0.629		0.000	0.629

[1] Non-fuel resources.

8.4 Overall LCIA – All Decking Products

Figure 8-1 compares the six impact categories plus the cumulative energy consumption, fresh water consumption, material resources consumption, and solid waste generated for the four decking products evaluated in the report on a percentage basis. Considerable differences existed between the redwood decking and the other decking materials evaluated. Redwood decking product had negative GWP values while the other decking materials have positive GWP values.

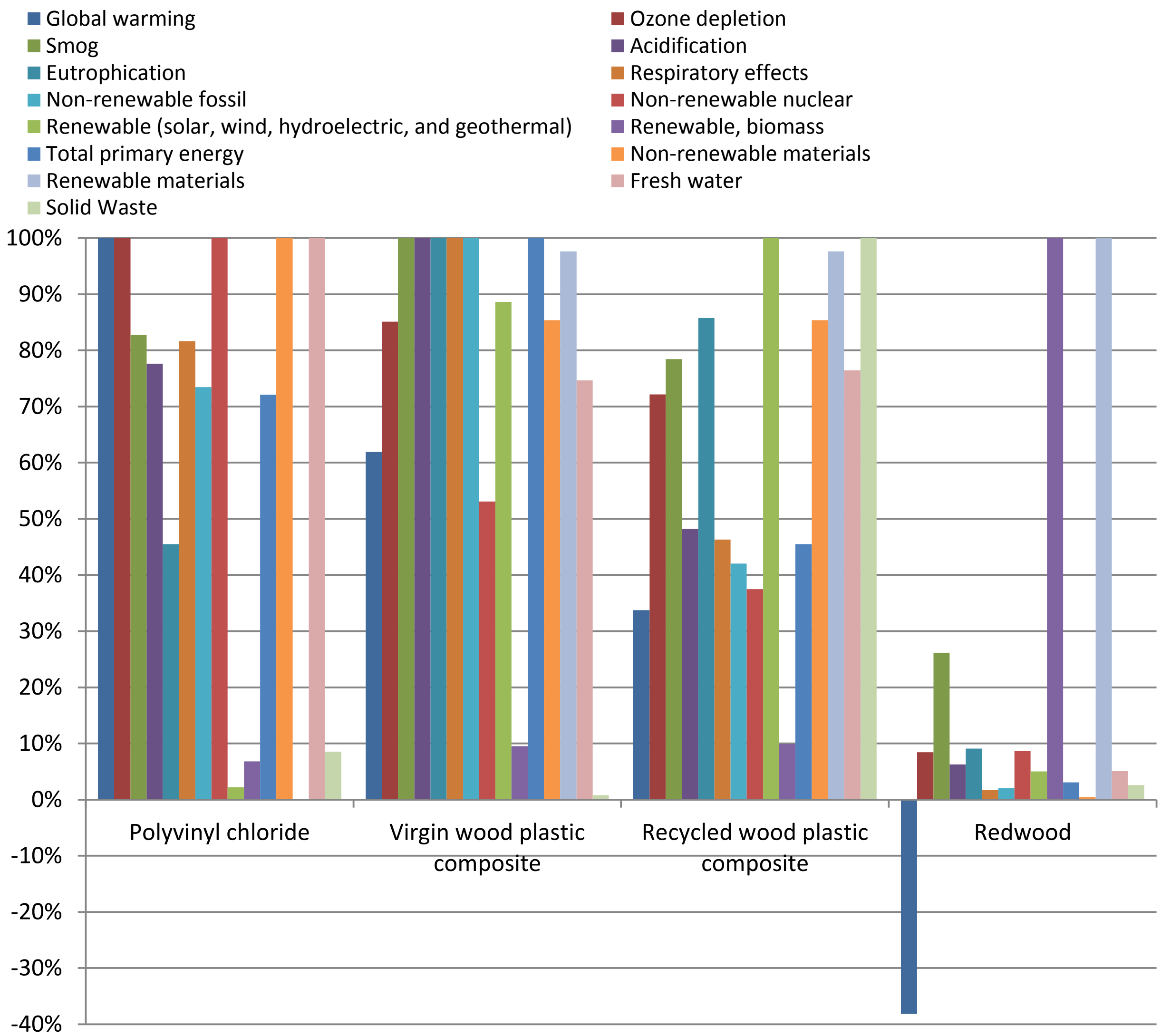

Figure 8-1: Life-cycle impact assessment for the four decking products by percentage

In addition, all other impact categories for redwood were less than 30% of the worst impact value reported. Reasons for the carbon benefit credited to the wood decking product was attributed to redwood decking lumber being primarily air-dried with only a minimal amount of kiln-drying being performed. Wood decking materials also stored the carbon that was originally absorbed by the growing tree as CO_2 from the atmosphere. Both WPC decking products also stored carbon. Overall, redwood decking had substantially less environmental impact over the other decking products with the exceptions of biomass energy and renewable material consumption. With respect to the other decking products, recycled WPC decking materials have the highest solid waste because of unusable waste during product manufacturing.

Table 8-17 shows the percentage values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste generated. **Table 8-18** displays the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste generated per 100 ft^2 of deck. **Table 8-19** shows the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste generated on a cubic meter basis.

PVC decking made the greatest contribution to GWP, ozone depletion, fresh water consumption, and non-renewable material resource consumption while virgin WPC decking had the highest smog, acidification, eutrophication, respiratory effects, and total primary energy. Recycled WPC had the highest solid waste production. As expected, redwood decking had the highest biomass energy consumption and renewable material resource consumption. Virgin and recycled WPC decking, however, nearly consumed as much renewable resources as redwood decking because these decking products were 50% wood. As previously mentioned, the biomass energy profile for redwood decking was low for a wood product, thereby not typical. In addition, GWP for redwood decking was negative as redwood decking stored the carbon while in service, which was originally sequestered by trees.

Table 8-17: Life-cycle impact assessment for four decking products by percentage per 100 ft^2 (9.29 m^2)

Impact category	Polyvinyl Chloride (%)	Virgin wood–plastic composite (%)	Recycled wood–plastic composite (%)	Redwood (%)
Global warming	100	62	34	–38
Ozone depletion	100	85	72	8
Smog	83	100	78	26
Acidification	78	100	48	6
Eutrophication	46	100	86	9
Respiratory effects	82	100	46	2
Primary energy consumption				
Non-renewable fossil	73	100	42	2
Non-renewable nuclear	100	53	37	9
Renewable (solar, wind, hydroelectric, and geothermal)	2	89	100	5
Renewable, biomass	7	10	10	100
Total primary energy	72	100	46	3
Material resources consumption[1]				
Non-renewable materials	100	85	85	0
Renewable materials	0	98	98	100
Fresh water	100	75	76	5
Waste generated				
Solid waste	9	1	100	3

[1] Non-fuel resources.

Biomass energy consumption was higher for redwood decking than for the alternatives, as expected, because wood product production typically utilizes the wood residue generated during production as a fuel source. Regardless, total energy for redwood was substantially lower than the other decking products: 4.2% (447/10640) of PVC, 3.0% (447/14700) of virgin WPC and 6.7% (447/6690) of recycled WPC. Captured biogenic methane from decomposing redwood decking in landfills to avoid natural gas production was 11.3 $m^3/100\ ft^2$, approximately 433 $MJ/100\ ft^2$ of energy.

The other impact measures indicated the high consumption of both non-renewable and renewable material resources in the virgin and recycled WPC decking products. WPC decking products are made of 50% polyethylene resins and 50% wood. In addition, WPC decking products are substantially heavier than the other decking products; therefore, these two products consume roughly the same as PVC in the non-renewable resource category and redwood decking in the renewable resource category.

Table 8-18: Life-cycle impact assessment for four decking products by value per 100 ft^2 (9.29 m^2)

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	426	264	144	-163
Ozone depletion	kg CFC-11 eq	1.60E-05	1.37E-05	1.16E-05	1.36E-06
Smog	kg O_3 eq	30.0	36.3	28.5	9.5
Acidification	kg SO_2 eq	4.61	5.94	2.86	0.21
Eutrophication	kg N eq	0.108	0.237	0.203	0.022
Respiratory effects	kg PM2.5 eq	0.276	0.338	0.157	0.006
Primary energy consumption	**Unit**				
Non-renewable fossil	MJ	10169	13840	5820	280
Non-renewable nuclear	MJ	449	238	168	39
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	614	693	35
Renewable, biomass	MJ	6	9	9	94
Total primary energy	MJ	10600	14700	6690	447
Material resources consumption[1]	**Unit**				
Non-renewable materials	kg	157	134	134	0.8
Renewable materials	kg	0	133	133	136
Fresh water	L	4500	3360	3440	229
Waste generated	**Unit**				
Solid Waste	kg	0.736	0.070	8.60	0.223

[1] Non-fuel resources.

Table 8-19: Life-cycle impact assessment for four decking products by value per m^3

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	1810	953	519	–460
Ozone depletion	kg CFC-11 eq	6.80E-05	4.93E-05	4.18E-05	3.83E-06
Smog	kg O_3 eq	127	131	103	27
Acidification	kg SO_2 eq	19.6	20.0	10.3	1.1
Eutrophication	kg N eq	0.457	0.856	0.734	0.061
Respiratory effects	kg PM2.5 eq	1.170	1.221	0.565	0.016
Primary energy consumption	Unit				
Non-renewable fossil	MJ	43100	50000	21000	790
Non-renewable nuclear	MJ	1900	860	610	110
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	65	2220	2500	98
Renewable, biomass	MJ	27	32	33	265
Total primary energy	MJ	45100	53100	24100	1260
Material resources consumption[1]	Unit				
Non-renewable materials	Kg	663	482	482	2
Renewable materials	Kg	0	480	480	385
Fresh water	L	19100	12100	12400	647
Waste generated	Unit				
Solid waste	Kg	3.12	0.25	31.0	0.63

[1] Non-fuel resources.

9 Sensitivity analysis—Mass Allocation

For the baseline scenario, redwood decking had 100% allocation of critical environmental impacts to the final product. To evaluate the significance of this original decision, a mass allocation was performed. The mass allocation only affected redwood decking as the other three alternatives had no co-products produced in conjunction with the decking. In essence, wood decking comprises 60% of the incoming log volume (wood only). If bark is considered, decking drops to 54.0%. Therefore, the following wood co-products produced as a direct result of sawing and planing were assigned positive and negative environmental attributes by mass:

- Sawing unit process – green redwood products and co-products
    - Decking (54.0%)
    - Wood chips (20.4%)
    - Sawdust (9.5%)
    - Bark (9.9%)
    - Shavings (1.7%)
    - Hog fuel (4.5%)

- Planing unit process
    - Planed (surface) dry decking (97.9%)
    - Dried planer shavings (2.1%)

Figure 9-1 shows the six impact categories plus cumulative energy consumption, fresh water consumption, material resource consumption, and solid waste generated for the four decking products evaluated on a percentage basis. As expected, no changes occurred for PVC, virgin WPC, and recycled WPC decking. All changes in impacts concerned redwood decking because of the change in allocation. Redwood decking GWP decreased slightly from the mass allocation case to the (no allocation) base case.

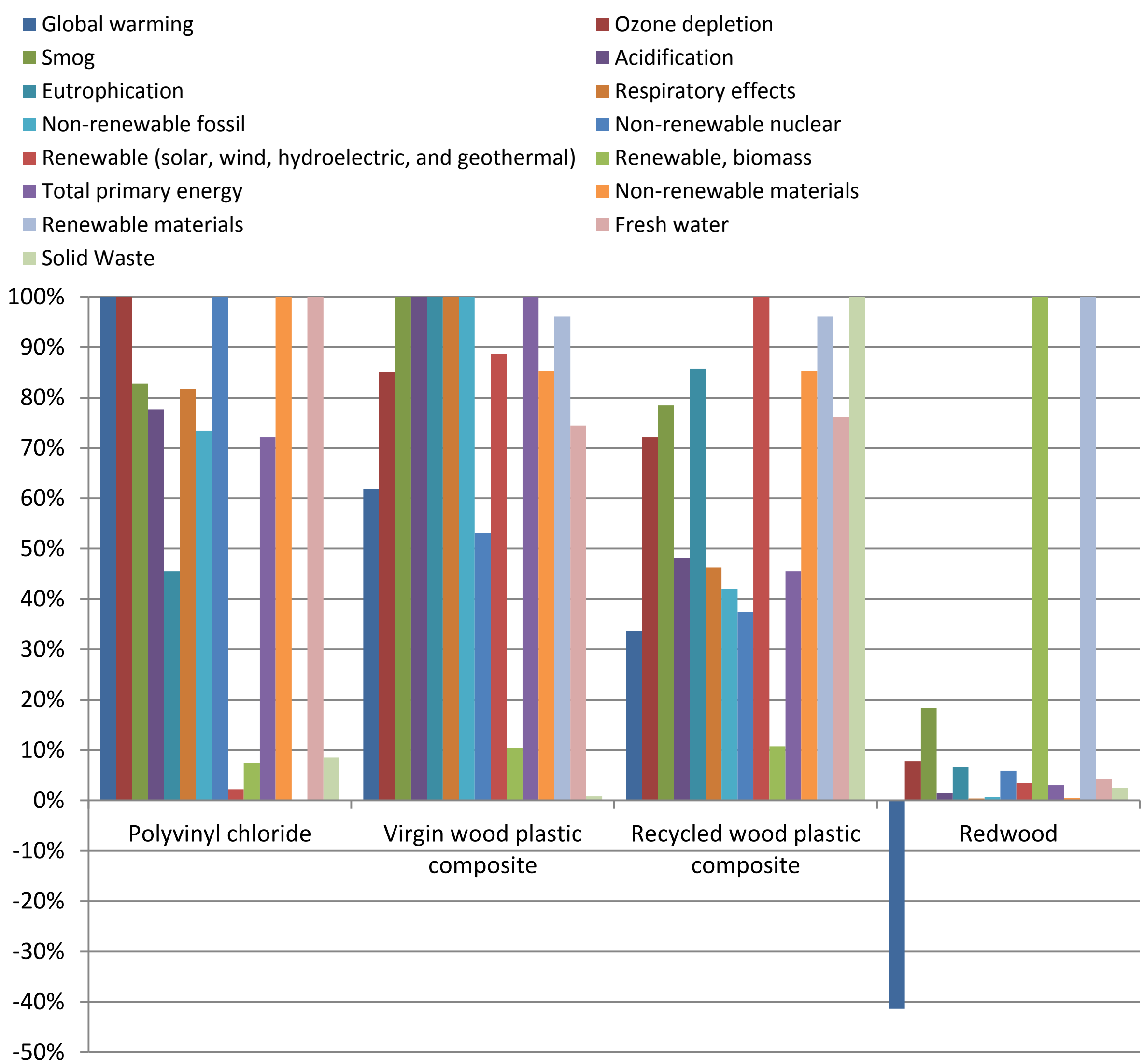

Figure 9-1: Life-cycle impact assessment for four decking products by percentage per 100 ft^2 (9.29 m^2) (Mass allocation).

Table 9-1 shows the percentage values for the six impact categories plus the cumulative energy, fresh water consumption, material resource consumption, and solid waste generated. **Table 9-2** displays the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste generated per 100 ft^2 (9.29 m^2) of deck. **Table 9-3** shows the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste on a cubic meter basis. PVC decking had the highest contribution to GWP and ozone depletion while virgin WPC decking has the highest contribution for smog, acidification, eutrophication, respiratory effects, and fossil energy. The biomass energy profile was not typical for redwood decking because of the low bioenergy consumption compared to other wood products (Puettmann et al. 2010). GWP decreased slightly to -175 kg CO_2-eq/100 ft^2 for the mass allocation case from -163 for the (no allocation) base case.

The other impact measures indicated the high consumption of both non-renewable and renewable material resources in the virgin and recycled WPC decking products, about the same as the no allocation case. WPC decking products are made of 50% polyethylene resins and 50% wood. In addition, WPC decking products are substantially heavier than the other decking products therefore these two products consume roughly the same as PVC in the non-renewable resource category and redwood decking in the renewable resource category.

Table 9-1: Life-cycle impact assessment for four decking products by percentage per 100 ft^2 (9.29 m^2) (Mass allocation)

Impact category	Polyvinyl Chloride (%)	Virgin wood–plastic composite (%)	Recycled wood–plastic composite (%)	Redwood (%)
Global warming	100	62	34	–41
Ozone depletion	100	85	72	8
Smog	83	100	78	18
Acidification	78	100	48	1
Eutrophication	46	100	86	7
Respiratory effects	82	100	46	0
Primary energy consumption				
Non—renewable fossil	73	100	42	1
Non—renewable nuclear	100	53	37	6
Renewable (solar, wind, hydroelectric, and geothermal)	2	89	100	3
Renewable, biomass	7	10	10	100
Total primary energy	72	100	46	3
Material resources consumption[1]				
Non—renewable materials	100	85	85	0
Renewable materials	0	98	98	100
Fresh water	100	75	76	4
Waste generated				
Solid waste	9	1	100	3

[1] Non-fuel resources.

Table 9-2: Life-cycle impact assessment for four decking products per 100 ft^2 (9.29 m^2) (Mass allocation)

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	426	264	144	–175
Ozone depletion	kg CFC-11 eq	1.60E-05	1.37E-05	1.16E-05	1.25E-06
Smog	kg O_3 eq	30.0	36.3	28.5	6.7
Acidification	kg SO_2 eq	4.61	5.94	2.86	0.09
Eutrophication	kg N eq	0.108	0.237	0.203	0.016
Respiratory effects	kg PM2.5 eq	0.276	0.338	0.157	0.001
Primary energy consumption	Unit				
Non-renewable fossil	MJ	10169	13836	5823	94
Non-renewable nuclear	MJ	449	238	168	27
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	614	693	24
Renewable, biomass	MJ	6	9	9	86
Total primary energy	MJ	10600	14700	6690	231
Material resources consumption[1]	Unit				
Non-renewable materials	kg	157	134	134	1
Renewable materials	kg	0	133	133	138
Fresh water	L	4500	3350	3430	189
Waste generated	Unit				
Solid Waste	kg	0.736	0.070	8.60	0.220

[1] Non-fuel resources.

Table 9-3: Life-cycle impact assessment for four decking products per m^3 (Mass allocation)

Impact category	Unit	Polyvinyl chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	1810	953	519	–493
Ozone depletion	kg CFC-11 eq	6.80E-05	4.93E-05	4.18E-05	3.54E-06
Smog	kg O_3 eq	127	131	103	19
Acidification	kg SO_2 eq	19.6	20.0	10.3	0.25
Eutrophication	kg N eq	0.457	0.856	0.734	0.045
Respiratory effects	kg PM2.5 eq	1.17	1.221	0.565	0.004
Primary energy consumption	Unit				
Non-renewable fossil	MJ	43100	49900	21000	267
Non-renewable nuclear	MJ	1900	860	610	80
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	65	2220	2500	67
Renewable, biomass	MJ	27	32	33	243
Total primary energy	MJ	45100	53000	24100	657
Material resources consumption[1]	Unit				
Non-renewable materials	kg	663	482	482	2
Renewable materials	kg	0	480	480	391
Fresh water	L	19100	12100	12400	533
Waste generated	Unit				
Solid waste	kg	3.12	0.25	31.0	0.62

[1] Non-fuel resources.

Total energy for redwood decking when assigning environmental impacts by mass dropped substantially from the base case. Total primary energy of 231 MJ/100 ft^2 (657 MJ/m^3) was found for the mass allocation, about a 50% drop from when allocating all environmental burdens to the final product and none to the wood residues.

10 Cradle-to-Gate Redwood Decking – Mass Allocation

In order for life-cycle assessments to meet the specifications outlined in the North American Structural and Architectural Wood Products product category rule (PCR), environmental burdens must be allocated on a mass basis (ISO 2006c; ISO 2007; FPInnovations 2011) unless co-product revenue differences exceed a 10:1 ratio in which case economic allocation should be used. In the case of redwood co-products, the revenue streams are similar and mass allocation is therefore used.

Table 10-1 shows the environmental impact measures associated with building a 100 ft^2- (9.29 m^2-) deck using a mass allocation basis. **Table 10-2** displays the measures generated on a cubic meter basis on a mass allocation from cradle-to-grave. One cubic meter of redwood decking was the declared unit. The tables show that the greatest environmental impacts occurred during the cradle-to-gate manufacturing process that included redwood resource harvesting and product production. The cumulated unallocated total energy consumption was 282 MJ/100 ft^2 (800 MJ/m^3) of deck with most of energy use associated with the cradle-to-gate manufacturing process. During final disposition, the biogenic methane captured avoided natural gas production and the resultant reduction of 461 MJ/100 ft^2 (1303 MJ/m^3) of energy was substantial. The biomass energy contributed 86 MJ/100 ft^2 (243 MJ/m^3) of deck to the total energy balance.

Table 10-1: Life-cycle impact assessment for 100 ft^2 (9.29 m^2) of redwood decking (Mass allocation)

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	–241	4.4	13.04	49	–175
Ozone depletion	kg CFC-11 eq	1.25E-06	1.69E-10	2.49E-09	2.54E-10	1.25E-06
Smog	kg O_3 eq	4.0	0.7	2.274	-0.34	6.7
Acidification	kg SO_2 eq	0.20	0.02	0.07	-0.21	0.09
Eutrophication	kg N eq	1.14E-02	1.48E-03	4.79E-03	–1.81E-03	1.58E-02
Respiratory effects	kg PM2.5 eq	1.18E-02	4.64E-04	1.45E-03	–1.24E-02	1.38E-03
Primary energy consumption	Unit					
Non-renewable fossil	MJ	319	59.9	177	–461	94.5
Non-renewable nuclear	MJ	26	0.5	1.5	–1.2	26.6
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	24	0	0	0	23.8
Renewable, biomass	MJ	86	0	0	0	86.1
Total primary energy	MJ	455	60	178	–462	231
Material resources consumption[1]						
Non-renewable materials	kg	1	0	0	0	1
Renewable materials	kg	136	0	0	0	136
Fresh water	L	99.59	0	88.85	0	188
Waste generated	Unit					
Solid waste	kg	0.220	0.000	0.000	0.000	0.220

[1] Non-fuel resources.

Table 10-2: Life-cycle impact assessment for one m^3 of redwood decking (Mass allocation)

Impact category	Unit	Cradle-to-Gate	Transportation to customer	Use phase	Landfill	Total
Global warming	kg CO_2 eq	-681	12	36.85	139	-493
Ozone depletion	kg CFC-11 eq	3.53E-06	4.76E-10	7.03E-09	7.17E-10	3.54E-06
Smog	kg O_3 eq	11.3	2.1	6.4	-1.0	18.8
Acidification	kg SO_2 eq	0.58	0.06	0.20	-0.59	0.25
Eutrophication	kg N eq	3.21E-02	4.18E-03	1.35E-02	-5.11E-03	4.47E-02
Respiratory effects	kg PM2.5 eq	3.34E-02	1.31E-03	4.09E-03	-3.50E-02	3.89E-03
Primary energy consumption	Unit					
Non-renewable fossil	MJ	901	169	500	–1303	267
Non-renewable nuclear	MJ	73	2	4	–4	75
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	67	0	0	1	68
Renewable, biomass	MJ	243	0	0	0	243
Total primary energy	MJ	1284	171	504	–1306	653
Material resources consumption[1]						
Non-renewable materials	kg	2.2	0	0	0	2.2
Renewable materials	kg	383	0	0	0	383
Fresh water	L	281	0	251	0	532
Waste generated	Unit					
Solid waste	kg	0.623	0.000	0.000	0.000	0.623

[1] Non-fuel resources.

Table 10-3 and **Table 10-4** show the environmental performance of 100 ft^2 (9.29 m^2) and 1 m^3 of redwood decking from cradle-to-gate including carbon stored in the final product, respectively. Forestry operations and wood production were derived from the cradle-to-gate LCIA shown in **Tables 10-1** and **10-2**. When compared to the environmental performance of redwood decking shown in **Table 8-15**, assigning environmental impacts by mass allocation lowers all of the environmental impact measures categorized in the present study as those burdens are allocated to chips and other co-products.

Table 10-3: Environmental performance of 100 ft^2 (9.29 m^2) of redwood decking from cradle-to-gate (Mass allocation)

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	–241	–262	14.2	6.6
Ozone depletion	kg CFC-11 eq	1.25E-06		1.25E-07	1.13E-06
Smog	kg O_3 eq	4.01		3.27	0.74
Acidification	kg SO_2 eq	0.204		0.141	0.063
Eutrophication	kg N eq	1.14E-02		6.66E-03	4.72E-03
Primary energy consumption	Unit				
Non-renewable fossil	MJ	319		215	104
Non-renewable nuclear	MJ	26		14.1	11.7
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	24		12.61	11.0
Renewable, biomass	MJ	86		9.30	76.8
Total primary energy	MJ	455		251	204
Material resources consumption[1]	Unit				
Non-renewable materials	kg	0.77		0.00	0.77
Renewable materials	kg	136		0	136
Fresh water	L	100		47	53
Waste generated	Unit				
Solid waste	kg	0.221		0.004	0.217

[1] Non-fuel resources.

Table 10-4: Environmental performance of 1 m^3 of redwood decking from cradle-to-gate (Mass allocation)

Impact category	Unit	Total	Forest carbon uptake	Forestry operations	Wood production
Global warming	kg CO_2 eq	–687	–738	40.1	10.9
Ozone depletion	kg CFC-11 eq	3.53E-06		3.533E-07	3.182E-06
Smog	kg O_3 eq	11.3		9.3	2.1
Acidification	kg SO_2 eq	0.577		0.398	0.179
Eutrophication	kg N eq	3.21E-02		1.881E-02	1.333E-02
Primary energy consumption	Unit				
Non-renewable fossil	MJ	901		606	295
Non-renewable nuclear	MJ	73		40	33
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	67		36	31
Renewable, biomass	MJ	243		26	217
Total primary energy	MJ	1290		708	580
Material resources consumption[1]	Unit				
Non-renewable materials	kg	2.2		0.0	2.2
Renewable materials	kg	385		0	385
Fresh water	L	281		132	149
Waste generated	Unit				
Solid waste	kg	0.623		0.011	0.612

[1] Non-fuel resources.

Scenario Analyses: end-of-life values from EPA (2006) data

The present LCA study conducted a sensitivity analysis assuming values from a wood LCA study conducted by Mahalle and O'Connor (2009) using EPA (2006) information. The assumptions are as follows: 1) wood decomposition rate, 23%, 2) methane capture equipment installed, 59%, 3) average capture efficiency, 75%, 4) energy recovery, 53% and 5) energy content of LFG, 0.54 MJ/m^3.

Figure 11-1 shows the six impact categories plus cumulative energy consumption, fresh water consumption, material resource consumption, and solid waste generated for the four decking products evaluated on a percentage basis. The only environmental impacts change occurred to the redwood decking and then only minimal changes occurred.

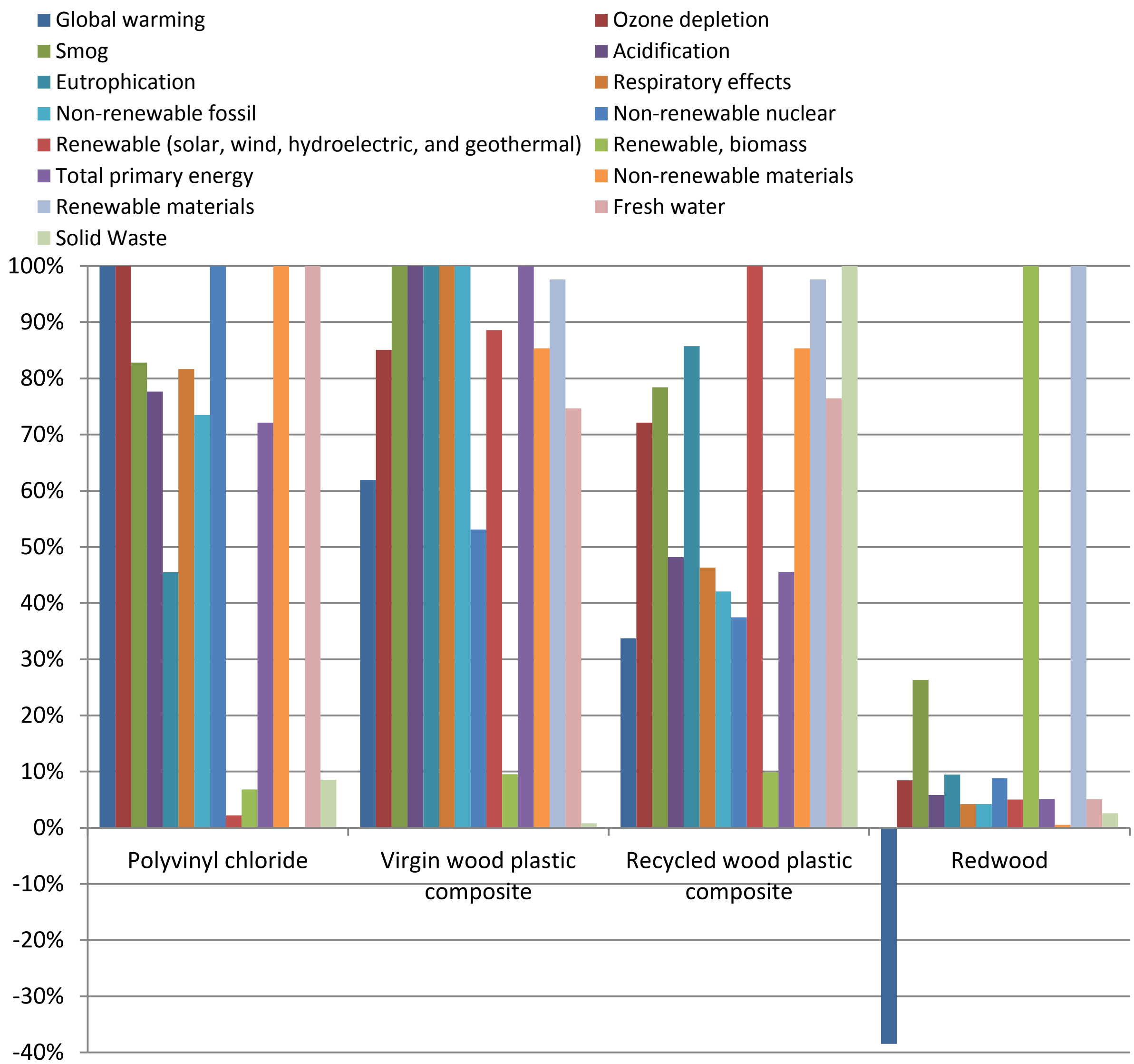

Figure 11-1: Life-cycle impact assessment for all decking by percentage (EPA 2006)

Table 11-1 shows the percentage values for the six impact categories plus the cumulative energy, fresh water consumption, material resource consumption, and solid waste generated. **Table 11-2** describes the LCIA for a functional unit of decking. As expected, the changes occurred in redwood decking because only redwood decking decomposed in the landfill. The GWP value using EPA (2006) data (–164 kg CO2-eq) was only slightly less than the GWP value estimated from the base case (–163 kg CO2-eq) shown in **Table 8-13**. **Table 11-2** displays the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste generated per 100 ft^2 of deck. **Table 11-3** shows the numerical values for the six impact categories plus cumulative energy, fresh water consumption, material resource consumption, and solid waste on a cubic meter basis. PVC decking had the highest contribution to ozone depletion and GWP, while virgin WPC decking has the highest contribution for smog, acidification, eutrophication, respiratory effects, and fossil energy. Only biomass energy consumed was higher for redwood decking than for any other product.

Table 11-1: Life-cycle impact assessment for four decking products by percentage per 100 ft^2 (9.29 m^2) (EPA 2006)

Impact category	Polyvinyl Chloride (%)	Virgin wood–plastic composite (%)	Recycled wood–plastic composite (%)	Redwood (%)
Global warming	100	62	34	–38
Ozone depletion	100	85	72	8
Smog	83	100	78	26
Acidification	78	100	48	6
Eutrophication	46	100	86	9
Respiratory effects	82	100	46	4
Primary energy consumption				
Non-renewable fossil	73	100	42	4
Non-renewable nuclear	100	53	37	9
Renewable (solar, wind, hydroelectric, and geothermal)	2	89	100	5
Renewable, biomass	7	10	10	100
Total primary energy	72	100	46	5
Material resources consumption[1]				
Non-renewable materials	100	85	85	0
Renewable materials	0	98	98	100
Fresh water	100	75	76	5
Waste generated				
Solid waste	9	1	100	3

[1] Non-fuel resources.

Table 11-2: Life-cycle impact assessment for four decking products per 100 ft^2 (EPA 2006)

Impact category	Unit	Polyvinyl Chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	426	264	144	–164
Ozone depletion	kg CFC-11 eq	1.60E-05	1.37E-05	1.16E-05	1.36E-06
Smog	kg O_3 eq	30.0	36.3	28.5	9.6
Acidification	kg SO_2 eq	4.61	5.94	2.86	0.35
Eutrophication	kg N eq	0.108	0.237	0.203	0.022
Respiratory effects	kg PM2.5 eq	0.276	0.338	0.157	0.014
Primary energy consumption	Unit				
Non-renewable fossil	MJ	10169	13836	5823	583
Non-renewable nuclear	MJ	449	238	168	40
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	15	614	693	35
Renewable, biomass	MJ	6	9	9	94
Total primary energy	MJ	10600	14700	6694	752
Material resources consumption[1]	Unit				
Non-renewable materials	kg	157	134	134	0.8
Renewable materials	kg	0	133	133	136
Fresh water	L	4500	3360	3440	229
Waste generated	Unit				
Solid Waste	kg	0.736	0.070	8.60	0.223

[1] Non-fuel resources.

Table 11-3: Life-cycle impact assessment for four decking products per m^3 (EPA 2006)

Impact category	Unit	Polyvinyl Chloride	Virgin wood–plastic composite	Recycled wood–plastic composite	Redwood
Global warming	kg CO_2 eq	1810	953	519	–463
Ozone depletion	kg CFC-11 eq	6.80E-05	4.93E-05	4.18E-05	3.83E-06
Smog	kg O_3 eq	127	131	103	27
Acidification	kg SO_2 eq	19.6	20.0	10.3	1.0
Eutrophication	kg N eq	0.457	0.856	0.734	0.063
Respiratory effects	kg PM2.5 eq	1.170	1.221	0.565	0.040
Primary energy consumption	Unit				
Non-renewable fossil	MJ	43100	49900	21000	1646
Non-renewable nuclear	MJ	1900	860	610	110
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	65	2220	2500	98
Renewable, biomass	MJ	27	32	33	265
Total primary energy	MJ	45100	53000	24100	2120
Material resources consumption[1]	Unit				
Non-renewable materials	kg	663	482	482	2
Renewable materials	kg	0	480	480	385
Fresh water	L	19100	12100	12400	647
Waste generated	Unit				
Solid waste	kg	3.12	0.25	31.0	0.63

[1] Non-fuel resources.

11 Conclusions and Recommendations

Based on the LCA developed for the four decking products, the following conclusions can be made. As shown by its negative GWP, the amount of carbon stored in redwood decking exceeds the total GHG emissions emitted during its whole life cycle. Other building products have this significant environmental advantage of storing carbon while in use to offset the impacts from making them: likewise the wood content of WPC products reduces their GWP burden relative to those products that have no carbon storage potential in the body of the product itself. The uptake of carbon dioxide from the atmosphere into the raw materials (i.e., trees) to make wood products and then storing the resultant carbon is a critical environmental benefit.

The substantial lower values across all six critical impact categories for redwood decking show its lower environmental footprint relative to alternative decking materials. Other life-cycle studies have shown similar results for wood products (Lippke et al. 2004; Werner and Richter 2007) relative to other building products with substantial fossil fuel inputs.

Less kiln–drying of wood products requires less energy consumption and creates lower environmental impacts. For alternative decking products, cradle-to-gate manufacturing consumes nine times more primary energy than is consumed for redwood decking. As shown by the present study and others (Milota et al. 2005; Puettmann and Wilson 2005), using wood products in the green form (i.e., not dried) suggest considerably lower environmental impact than kiln–drying wood to the desired MC. Utilizing less energy-intensive methods of drying wood in place of heated kilns can result in huge reductions in environmental impact.

A trade-off exists between landfilling old wood products and capturing the biogenic methane to avoid natural gas production. Capturing biogenic methane from decomposing wood avoids natural gas production which is a substantial environmental benefit for low-energy intensive wood products. If the methane is released it contributes to GWP, an environmental cost.

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13 Appendix: Forest Resources Module Survey

The California Redwood Association (CRA) is sponsoring a research project designed to evaluate the environmental impacts associated with the manufacture, consumption, disposal, and re-use of redwood as a decking material in comparison to wood–plastic composites. The objective of this project is to provide a transparent, scientifically verified, non-biased assessment which allows consumers to compare the environmental impacts between these two products. This assessment can be used to develop marketing strategies aimed at correcting misperceptions about the environmental impact of wood as a building material through a "cradle-to-grave" (raw material extraction to waste disposal) analysis.

This study is conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM) which is a non-profit research consortium with members from 16 universities and research institutions. Analyses will determine redwood decking's contribution to cumulative energy consumption, air pollution, water pollution, solid waste pollution, and climate change relative to competing decking products. The project is broken into three interconnected modules that collectively provide the CRA with the necessary elements to support environmental claims in their marketing efforts: 1) market assessment, 2) forest resources, and 3) manufacturing process.

The forest resources module will describe typical harvest activities reflecting the costs and burdens associated with supplying logs for processing by redwood decking manufacturers. Other objectives of the module include development of representative data describing forest management and harvest activities associated with the growth, removal, and reestablishment specific to the redwood forest types. Within the questionnaire we will be asking questions on stand establishment, harvesting system and productivity.

We would greatly appreciate it if you could complete and return the questionnaire at your earliest convenience. ***Any information that you provide will be kept strictly confidential, and will only be released as a summary where no individual's answers can be identified.*** The information collected from this survey will be destroyed upon completion of the study. Of course, if you have any questions, please contact us at the address or phone numbers shown below.

Sincerely,

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Part I. Stand Establishment and Forest Inventory

1. Planting production rates and seedling types

    - Seedling type: Bare root __________ Container _____________ 1.0 / 2.0 / other
    - Planting rates (trees/day-planter):____________________________
    - Trees/acre:____
    - Number crew/transport vehicle: _____________________________________
    - Average distance to planting site (miles): ____________________

2. Detail on stand establishment and yield is used to identify the inputs and outputs necessary to produce the per acre yield typically removed from redwood forests. The yield figures are then used to determine emission profiles per unit of wood volume.

Silviculture System		Volume removed per entry/acre	Rotation or re-entry period (years)	Volume remaining post harvest/acre	Site Prep	Planting	
Type	(%) area or volume (circle which)				Y/N[a]	Y/N	TPA[b]
Clearcut							
Partial cut							
Coppice							
Shelterwood							
Seed tree							
Other							

[a]Eight slash treatment types are listed on Page 14
[b]TPA: trees per acre

3. Please indicate "Yes" or "No" as applicable to your company and provide additional details where applicable.

Treatment	Y/N	# entries/ rotation	Comments			
Fertilization			(fertilizer mix and application rate/acre)			
Pre-commercial Thinning			Equipment type	Production rates (ac/day) per person or machine	#people or machines	TPA removed/ final density

Part II. Harvesting Systems and Productivity

1. Please estimate your company's redwood harvest in 2010.
Sawtimber: _______________ MBF/acre and/or _______________ Cubic feet/acre
    - Clearcut:__________ MBF/acre; Thinning _____________ MBF/acre

Other products from the redwood harvest areas: specify them if any: (e.g. non-redwood sawtimber or biomass for energy)
______________________: _______________ MBF/acre and/or _______________ Cubic feet/acre
    - Clearcut:____________ MBF/acre; Thinning ____________MBF/acre

2. Please provide average values for harvested trees
DBH _________inches; Total height __________feet; Utilization limit (top diameter) _________inches
Utilized log length: Minimum___________ ft; Maximum: ______________ft

3. Please estimate the percentage volume of redwood harvest that originated from each land ownership group. **Total = 100%**

Company lands_________%; Other private lands_________%; State__________%
Federal_________%; Tribal lands_________%

4. What are typical external skidding/yarding distances (average distance between a landing and a harvest unit boundary)?

Skidding _____________ ft; Shoveling _____________ ft; Skyline _____________ ft
Helicopter ____________ft: Other ____________ ft (specify:_________________________)
Other ___________ ft (specify:_______________________________________)

5. Please list equipment used and estimate the percentage of their use for the following operations, manual (using a chainsaw) versus mechanized based on your annual harvest volume. **Total = 100%**

Harvesting Operation	**Manual**		**Mechanized**		**Total**
	Equipment used		**Equipment used**		
Clearcut					
Felling	Chainsaw	%		%	100%
Limbing/Bucking	Chainsaw	%		%	100%
Thinning/Selection					
Felling	Chainsaw	%		%	100%
Limbing/Bucking	Chainsaw	%		%	100%

6. Please list harvesting equipment options and systems that are commonly used to harvest redwood and estimate an annual harvest volume (%) using each harvesting system in your company.

--- Clearcut ---

Harvesting System	**Harvesting Phase**				**Harvest Volume /year**
	Felling	**Primary transport***	**Processing**	**Loading**	
Ground-based system					
					%
					%
					%
					%
					%
Skyline yarding system					
					%
					%
					%
					%
Helicopter yarding system					
					%
					%
					%
Others (please specify)					
					%
					%
					%
					%
Total timber harvest volume per year from clearcut					**100%**

*Primary transport: transporting logs or whole trees from the stump to landing or roadside

7. Please list harvesting equipment options and systems that are commonly used to harvest redwood and estimate an annual harvest volume (%) using each harvesting system in your company.

--- Commercial Thinning ---

Harvesting System	Harvesting Phase				Harvest Volume /year
	Felling	Primary transport*	Processing	Loading	
Ground-based system					
					%
					%
					%
					%
					%
Skyline yarding system					
					%
					%
					%
					%
Helicopter yarding system					
					%
					%
					%
Others (please specify)					
					%
					%
					%
					%
Total timber harvest volume per year from commercial thinning					**100%**

*Primary transport: transporting logs or whole trees from the stump to landing or roadside

Harvesting Machine Specifications

<u>Please fill the table with your best estimates. You ONLY need to provide information for equipment options that are commonly used in your harvesting operations.</u>

<u>Felling</u>

TYPE OF MACHINE	Machine Size /Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Clearcut						
Chainsaw						
Feller-Buncher						
(Other: specify)						
(Other: specify)						
Thinning						
Chainsaw						
Feller-Buncher						
(Other: specify)						
(Other: specify)						

<u>Note:</u>

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horsepower and small/medium/large
- Potential Production Rate (MBF/hour): <u>felling only</u>. Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits.
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

<u>Processing</u>

TYPE OF MACHINE	Machine Size/ Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Clearcut						
Chainsaw processing						
Stroke-boom delimber						
Dangle-head processor						
Other (specify):						
Other (specify):						
Thinning						
Chainsaw processing						
Stroke-boom delimber						
Dangle-head processor						
Other (specify):						
Other (specify):						

<u>Note:</u>

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horsepower and small/medium/large
- Potential Production Rate (MBF/hour): <u>Processing only</u>. Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits.
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on teh total amount of fuel used per day divided by the total number hours per day in a typical operation.

Ground Skidding and Forwarding Equipment: Clearcut

TYPE OF MACHINE	Machine Size / Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Wheeled Skidders						
Skidder						
Tracked Skidders						
Crawler						
Shovels						
Shovel						
Others: Please specify						

Note:

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horsepower and small/medium/large
- Potential Production Rate (MBF/hour): stump to landing (primary transport). Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits.
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

<u>Ground Skidding and Forwarding Equipment:</u> Thinning

TYPE OF MACHINE	Machine Size / Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Wheeled Skidders						
Skidder						
Tracked Skidders						
Crawler						
Shovels						
Shovel						
Others: Please specify						

<u>Note:</u>

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horsepower and small/medium/large
- Potential Production Rate (MBF/hour): stump to landing (primary transport). Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits.
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

<u>Cable and Aerial Yarding Equipment:</u> Clearcut

TYPE OF MACHINE	**Machine Size / Horsepower /Description**	**Potential Production Rate (MBF/hour)**	**Hourly Machine Cost ($/hour)**	**Labor Cost ($/hour)**	**Machine Efficiency (%)**	**Fuel use (gal/hour)**
Skyline						
Skyline yarder						
Helicopters						
Helicopter						
Others: Please specify						

<u>Note:</u>

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horse power, yarder tower height, maximum external payload capacity for helicopter (small/medium/large)
- Potential Production Rate (MBF/hour): stump to landing (primary transport). Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits <u>for all yarding crew</u> (yarder operator, loader operator if any, landing crew, rigging crew, choker setters).
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

<u>Cable and Aerial Yarding Equipment:</u> Thinning

TYPE OF MACHINE	Machine Size / Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Skyline						
Skyline yarder						
Helicopters						
Helicopter						
Others: Please specify						

<u>Note:</u>

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horse power, yarder tower height, maximum external payload capacity for helicopter (small/medium/large)
- Potential Production Rate (MBF/hour): stump to landing (primary transport). Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits <u>for all yarding crew</u> (yarder operator, loader operator if any, landing crew, rigging crew, choker setters).
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

Sawlog Loading Equipment

TYPE OF MACHINE	Machine Size / Horsepower /Description	Potential Production Rate (MBF/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Loading						
Loader						

Note:

- Type of Machine: make multiple listings of the same machine type if the same type of machine but with different size/horsepower is used.
- Machine Size/Description: horse power and clearcut only, thinning only, or both.
- Potential Production Rate (MBF/hour): sawlog loading productivity. Alternatively, daily production (MBF/day) may be provided along with the number of hours/day of working.
- Hourly Machine Cost ($/hour): this includes fixed costs (e.g. depreciation, insurance,…) and operating costs (e.g. fuels, repair/maintenance,…), but does not include the operator's wages.
- Labor Cost ($/hour): Labor includes base labor rate plus fringe benefits.
- Machine Efficiency (%): amount of time that a machine is actually used to produce timber per day or hour, excluding machine warming up, breaks, fueling, downtime, etc.
- Fuel Consumption (gal/hour): this may be estimated based on the total amount of fuel used per day divided by the total number hours per day in a typical operation.

Move-in/Move-out Equipment

TYPE OF MACHINE	Machine Size (horse power)	Loading/ Unloading time (min./trip)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Average Round-Trip Time (min./machine)	Fuel use (gal/hour)
Move-in/Move-out – Logging and Biomass Recovery Equipment						
Low-bed						
Other (specify):						

- Low-beds (or low-boys) are commonly used to bring logging and biomass recovery equipment to harvesting sites. Please provide you best estimates.

PART III. LOG TRANSPORTATION

TYPE OF MACHINE (Trucks)	Machine Size (horse power)	Average Load (MBF/trip)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Loading/ Unloading time (minutes)	Fuel use (gal/hour)

Hauling distances and average speeds by forest road type

Road Type	Mileage (one-way distance) (miles)	Average Truck Speed (miles/hour)
Spur		
1- or 2-lane dirt road		
1- or 2-lane gravel road		
2-lane highway		
Interstate freeway		

- Spur: Unimproved temporary dirt spur within harvest unit.
- 1 or 2-lane dirt road: Single or double lane seasonal dirt road primarily constructed with native soils.
- 1 or 2-lane gravel road: Single or double lane permanent road primarily surfaced with gravel.
- 2-lane highway: Local highway paved with asphalt or concrete.

PART IV. SLASH TREATMENTS

Please indicate "Yes" or "No" to each "treatment types (0 thru 8)" and "fill out" the table below based on descriptions on the slash treatment types.

Descriptions on eight slash treatment types:

Treatment type	Slash Treatment description	Yes	No
0	No slash disposal conducted		
1	Whole tree harvest operation with piling at landing		
2	Whole tree harvest operation with piling at landing and piling in woods		
3	Whole tree harvest operation with piling at landing and broadcast burn		
4	Bole-only harvest operation with piling in woods		
5	Bole-only harvest operation with broadcast burn		
6	Processing of biomass piled at landing		
7	Recovery and processing of biomass left in the woods		
8	Processing biomass at landing PLUS recovery of biomass in woods		

Indicate only those that apply for your slash treatment type or N/A if not applicable	%
Percent of cut stem utilized (net out decay and breakage)	
Percent of residue delivered to landing	
Percent of residue delivered to landing recovered	
Percent of residue piled in woods in whole tree	
Percent of wood piled in woods or recovered in bole only	
Percent of dry wood consumed in pile burning	
Percent of dry wood consumed in broadcast burn	

Logging system used to harvest sawlogs	**Slash treatment type**	**Biomass recovery system if slash is recovered (select letter(s) from the Note)**
Ground-based		
Skyline Yarding		
Helicopter Yarding		

Note:

A. Biomass from Landing Slash Direct to Mill
B. Biomass from Landing through Intermediate Load Site (Concentration Yard)
C. Biomass Recovery across Harvest Units through Intermediate Load Site

V. BIOMASS RECOVERY EQUIPMENT - Production Units in Green Ton (GT)

- What is moisture content (%) measured when slash is ground or chipped? ____________%
- What is a total amount of biomass harvesting from the redwood-dominant forests in 2010? ________________ ton or ft^3

Please provide names in general term (no make/model) of biomass recovery equipment and systems that are commonly used to utilize forest residues left from redwood sawlog harvesting or other forest management activities (e.g. precommercial thinning) and estimate an annual recovery volume (%) using each recovery system in your company. **Total = 100%**

- **Biomass from Landing Slash Direct to Mill**

Biomass Operations Phase			Biomass harvest /year
Loading	Grinding or Chipping	Loading (if needed)	
			%
			%

- **Biomass from Landing through Intermediate Load Site (Concentration Yard)**

Biomass Operations Phase				Biomass harvest /year
Loading	Pre-hauling	Grinding or Chipping at a centralized processing site	Loading (if needed)	
				%
				%

- **Biomass Recovery across Harvest Units through Intermediate Load Site**

Biomass Operations Phase				Biomass harvest /year
Loading	Pre-hauling	Grinding or Chipping at a centralized processing site	Loading	
				%
				%

Biomass Harvesting Productivity and Cost

Please list names of machine types if the machines listed in the table below are different from the machines that are commonly used in your biomass operations. Please be sure to include machine description and horsepower information.

TYPE OF MACHINE	Machine Size / Horsepower /Description	Potential Production Rate (ton or yd^3/hour)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Machine Efficiency (%)	Fuel use (gal/hour)
Processing Equipment						
On-site horizontal grinder						
Centralized horizontal grinder						
Small whole tree chipper						
Medium whole tree chipper						
Large whole tree chipper						
Other:						
Loading - Piling Equipment						
Loader for Pre-hauling						
Loader for feeding biomass						
Front-end loader						
Other:						

Note:

- On site grinding: landing slash will be ground at landing or roadside near or at landings. No pre-hauling or compiling of slash using modified dump truck, roll-on/off container or hook-lift trucks is performed.

- Centralized grinding: a grinder is located in a centralized grinding location where logging slash and sub-merchantable size whole trees are compiled using modified dump truck, roll-on/off container or hook-lift trucks.

Biomass Transportation

Please list names of machine types if the trucks listed in the table below are different from the machines that are commonly used to haul biomass fuels from a grinding location to energy plants/sawmills. Please be sure to include machine description and horsepower information.

TYPE OF MACHINE	Truck Capacity (green tons or yd^3/trip)	Average Load (ton/trip)	Hourly Machine Cost ($/hour)	Labor Cost ($/hour)	Loading/ Unloading time (minutes)	Fuel use (gal/hour)
Chip van (140 yd^3)						
Chip van (120 yd^3)						
Dump truck-modified						
End-dump trailer						
Roll-off or Hook-lift truck						
Other:						
Other:						

Note:

- When a centralized grinding is used, end-dump trailers, modified dump truck, roll-on/off, and hook-lift truck to deliver slash from harvesting sites and landings to a centralized grinding location.

Hauling distances and average speeds of chip vans by forest road types

Road Type	Mileage (one-way distance) (miles)	Average Chip Van Speed (miles/hour)
Spur		
1- or 2-lane with no rocks		
1- or 2-lane gravel		
2 lane highway		
Interstate		

14 Appendix: Product Manufacturing Module Survey

Thank you for giving us the opportunity to work with you on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be an excellent marketing tool for the redwood decking industry particularly in the green building industry. A growing demand for building projects that use products with lower environmental burdens and energy-efficient materials has spurred a green movement in the construction industry.

As a member of the U.S. forest products industry, you know that using wood is a sensible choice because wood is renewable and often poses fewer burdens to the environment than substitute materials. Many consumers do not understand this. With your input, we can test the theory that redwood decking poses less negative impacts to the environment than substitute materials such as plastic decking do. Completed projects of this type have shown other wood products to be a sustainable and sound environmental choice over product alternatives.

This questionnaire focuses on annual production, annual energy use and generation, annual material inputs and outputs, and annual environmental emissions for redwood decking manufactured in California. Regarding the questionnaire, our focus is on process information because this data is vital for precise and accurate results. Details harder to report may be requested later. We realize that you may not have all the information requested, but the data you are able to provide will be appreciated. **Strict confidentiality will be maintained for all companies that supply data. The focus of the project is 2x6 decking.**

Company Name: ________________________________

Facility Address: ________________________________

____

Contact Person: ________________________________

Telephone: ( ) **Fax:** ( )_______

Contact email: ________________________________

Please direct questions and send complete questionnaires to:

Rick Bergman
USDA FS Forest Products Laboratory
One Gifford Pinchot Dr
Madison, WI 53726-2398
Phone (608) 231-9477 / Fax (608) 231-9508
Email: rbergman@fs.fed.us

PART I: OPERATION OVERVIEW

GENERAL INFORMATION (Please provide responses for all requested information)

Reporting Year: ________ Starting Month: ________ Ending Month: ________

Log scale: Doyle, International, Scribner, Weight basis (circle one)

How many days did your mill operate for the selected reporting year? _________Days/Year

How many production shifts per day for the selected reporting year? __________Shifts/Day

Does your mill have the following:

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

PART II: TOTAL MILL MATERIAL & ENERGY INPUTS & OUTPUTS

Average log diameter: ____________ inches

Range of log diameter: ______to______ inches

Average log length: ______________feet

Volume of incoming logs during the reporting year: _____________ thousand bf

Volume of logs sold to outside firms during the reporting year: _________ thousand bf

Volume of logs sent to your sawmill during the reporting year: ________ thousand bf

Please complete the following table to provide your facilities annual lumber/decking production levels for the reporting year by product size. Please add more rows if necessary. Note – only report rough green lumber production by size for products when sold or transferred from your facility. We will be completing a mass balance (logs in vs. lumber/decking and co-products out) for your mill, so we first need to know your lumber production – so if it leaves your facility, we need to track it. *We provided an example in the table of a mill that produces annually 60 million bf of nominal 2x6s. The numbers for 2x6 decking are the focus of this project but we need values for the other sizes to determine the mass balance accurately.*

ANNUAL MILL PRODUCTION

Nominal Lumber Size	MMbf for reporting yr.	Surfaced-Green (MC=30%)[1]	Rough-Dry (MC=15%)[1]	Surfaced-Dry (MC=15%)[1]	Rough Green (Sold or transferred only) (MC=30%)[1]	Price ($/Mbf)	Percentage (%)
2x6	e.g. 45	X, MC=35%				e.g.600	75%
2x6	e.g. 10		X, MC=19%			e.g.700	16.7%
2x6	e.g. 5			X, MC=19%		e.g.900	8.3%
Total	e.g. 60	e.g.45	e.g. 10	e.g. 5		e.g.640	100%
Please complete for your mill below (add more rows if required)							
1x4							
1x4							
1x4							
5/4x6							
5/4x6							
5/4x6							
2x4							
2x4							
2x4							
2x6							
2x6							
2x6							

[1] Change MC as appropriate More rows on next sheet (over)

Nominal Lumber Size	MMBF for reporting yr.	Surfaced-Green (MC=30%)[1]	Rough-Dry (MC=15%)[1]	Surfaced-Dry (MC=15%)[1]	Rough Green (Sold or transferred only) (MC=30%)[1]	Price ($/MBF)	Percentage (%)
2x8							
2x8							
2x8							
2x10							
2x10							
2x10							
2x12							
2x12							
2x12							
2x14							
2x14							
2x14							
4x4							
4x4							
4x4							
4x6							
4x6							
4x6							
4x8							
4x8							
4x8							
Other							
Other							
Other							
Other							
Other							
Other							
Total							100%

[1] Change MC as appropriate

ANNUAL RESOURCE TRANSPORTATION DATA: (transporting material to and from your sawmill)

Material	No. of deliveries	Average net weight of load (tons)	Average one-way distance (miles)	Transportation type (choose one)	Percent empty backhaul
Logs				Rail/Trucking	
Purchased wood fuel (if any)				Rail/Trucking	
2x6 redwood decking				Rail/Trucking	
Boiler Chemicals				Small/Large Truck	

For each of the co-products produced at your plant, please indicate the weight (tons) of **annual** production for the reporting period that are shipped to other users, used internally as fuel or for the production of another co-product at your facility, stockpiled for future use or land filled (estimates are acceptable). If zero, enter a dash (-). Please state units if other than tons like cubic yards. The final column (Total Quantity) should equal the sum of the individual rows.

Estimate amount of wood residue produced per thousand bf of redwood decking _____tons/Mbf

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

If you have installed emission control devices at your mill, please list them by type and the equipment controlled by the device.

	Boiler #1	Boiler #2	Sawmill	Dry Kiln	Planermill	Logyard
Type of Device						
Equipment controlled						
Electrical Use[1], kWh						
Type of emissions controlled						

Are you processing material from other facilities (e.g. kiln–drying lumber or planing rough green or kiln–dried lumber from other mills)?

_________Yes; ___________No;

If Yes, please specify the quantity per process for the selected reporting year:
Kiln–drying lumber from other mills (MMbf/yr) _______
Planing rough green lumber from other mills (MMbf/yr) _______
Planing kiln-dried lumber from other mills (MMbf/yr) _______

Short description of redwood decking production process:
The sawmill complex is divided into six process units: (1) log yard, (2) sawing, (3) drying, (4) planing, (5) boiler or co-generation equipment (energy generation) and (6) emission control (if applicable)
- Log yard includes all log handling from receiving logs at mill gate up to breakdown of the log
- Sawing includes the breakdown of the logs into rough green lumber.
- Drying includes stickering , the dry kilns, loading area, and unloading (storage) and air yards.
- Planing includes the unstacker, planer, and packaging areas. Each of these includes transportation to the next unit process or plant gate.
- Boiler/co-generation equipment (energy generation) includes fuel storage, transportation, boiler, turbines and steam distribution system.

ANNUAL TRANSPORTATION FUEL USE ON-SITE (includes all fuels for yard equipment, forklifts, and carriers)

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		Log yard	Sawing	Drying	Planing	Boiler/Co-gen	
Off-road diesel							Gallons
Fuel Oil #6							Gallons
Propane							Gallons
Gasoline							Gallons
Electricity							kWh
Other							

ANNUAL BOILER FUEL AND ELECTRICTY USE: (boilers, cogeneration units, etc.)

Boiler Fuel	Total Quantity	Units	Moisture content (if applicable)
Wood			
Wood boiler fuel produced on-site		Tons	
Purchased wood boiler fuel		Tons	
Fossil Fuel			
Natural Gas		Thousand ft^3	
Fuel oil #1(kerosene)		Gallons	
Fuel oil #2 (heating oil)		Gallons	
Fuel oil #6		Gallons	
Propane		Gallons	
Electricity for entire facility		kWh	
Other			

ANNUAL ELECTRICITY USE (Estimation by percentage or number is ok)

Process	kWh	% of total
1. Log yard		
2. Sawing		
3. Kiln–drying		
4. Planing		
5. Boiler/Co-generation		
Total		100%

ANNUAL WATER USE

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		Log yard	Sawing	Drying	Planing	Boiler/Co-gen	
Input							
Surface water							Gallons
Groundwater							Gallons
Municipal water							Gallons
Output							
Water discharged							Gallons
Water recycled							Gallons

What percent of water is recycled? ________%

ANNUAL ANCILLARY MATERIALS

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		Log yard	Sawing	Drying	Planing	Boiler/Co-gen	
Hydraulic Fluid							Gallons
Motor Oils							Gallons
Greases							Pounds
Gasoline							Gallons
Steel strapping							Pounds
Plastic strapping							Pounds
Paint							Gallons
Corrugated cardboard							Pounds
Replacement stickers							Pounds

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

Type	Pounds	Percent Landfilled
Pallets (not re-used)		
Fly Ash		
Bottom ash		
General refuse (do not include above materials)		
Recycled material		
Other		

ANNUAL AIR EMISSIONS: (Provide stack test if available)

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		Log yard	Sawing	Drying	Planing	Boiler/Co-gen	
Dust							Pounds
Total Particulate							Pounds
PM2.5							Pounds
PM10							Pounds
Carbon monoxide (CO)							Pounds
Carbon dioxide (CO_2)							Pounds
Acetone							Pounds
Acetaldehyde							Pounds
Formaldehyde							Pounds
Hazardous Air Pollutants (HAPS)							Pounds
Methanol							Pounds
Nitrous oxides (NOx)							Pounds
Phenol							Pounds
Propionaldehyde							Pounds
Sulfur dioxide (SO_2)							Pounds
Total VOCs							Pounds
Others (please list all known):							Pounds
Other							Pounds
Other							Pounds
Other							Pounds
Other							Pounds

ANNUAL BOILER CHEMICALS

Boiler Chemicals	Total Quantity	Units
Oxygen scavenger Name_____________		Gallons
Corrosion inhibitors Name_____________		Gallons
Scale inhibitors Name_____________		Gallons
pH adjusters Name_____________		Gallons
Anti-foams Name_____________		Gallons
Sludge conditioners Name_____________		Gallons

ANNUAL WATER EFFLUENT: (Provide water discharge test if available)

Type	Total Quantity	Percent of total by unit process (percentage or volume)					Units
		Log yard	Sawing	Drying	Planing	Boiler/Co-gen	
BOD[1]							Pounds
COD[2]							Pounds
Chlorine							Pounds
Oil							Pounds
Suspended solids							Pounds
Dissolved solids							
Phenols							Pounds
Others (please list all known):							Pounds

[1] Biological oxygen demand
[2] Chemical oxygen demand

DRY KILN INFORMATION (dry kilns are the most energy intensive process for making decking/lumber)

Part of this study will be reviewing energy reduction potentials associated with kiln-drying, the most energy intensive aspect of lumber production. Please provide the following details on each of your kilns. If all or some kilns are identical simply write "same as Kiln No. X" below the appropriate kiln number. Attach a separate sheet if there are more than 5 kilns.					
Dry Kilns	1	2	3	4	5
Kiln Capacity (Mbfm)					
Energy System					
Direct-fired					
Fuel type (gas, oil, biomass, etc.)					
Capacity (BTU's / hr.)					
Total HP electrical motors (blower, make-up air etc.)					
Radiant Heating (coils)					
Type (steam, hot oil, hot water)					
Kiln Configuration(side loading, single track, double track)					
Average age of kilns or year installed					
Fan Configuration (line shaft, cross shaft)					
No. of fan motors					

Dry Kilns (continued)	1	2	3	4	5
Total HP for Kiln					
Humidification System (yes/no)					
If **yes**, state type (live steam, water spray)					
Vent Heat Exchangers present (Yes/No)					
Drying Practices					
Initial Moisture Content					
Average length of time material remains in air-drying yard (days)					
Average Kiln–drying Time for all material (hrs)					
Pre-sorting (Yes/No)					
If **Yes**, state type of sorting (by MC, grade, other)					
Final Moisture Content					

Glossary

Baghouse: Air pollution device which forces gases through a filter thereby capturing gas born particles.
BOD
By-product: Material produced during manufacturing that is recycled or used "within system boundaries."
Bottom ash: Residual by-product of burning coal. Porous, grainy, roughly sand sized particles.
Co-product: A material produced from manufacturing and "sold outside of the system boundary."
Cyclone: A device that uses centrifugal forces to collect waste material.
Dust: Dispersion particles formed in grinding a solid; particles may be small enough to temporarily suspend in the air.
Edgings: Pieces of board produced after lumber passes through an edger to achieve desired width.
Electrostatic Precipitator (esp): A type of precipitator which changes the electrical charge on a particle so that it can be captured by electrostatic forces.
Emissions: Expulsion of pollutants to air from a source.
Fly ash: Particulate impurities that come from burning coal and other materials.
General refuse: Waste collected from the facility that is mixed with dirt and cannot be sent to the boiler.
HAPs: Hazardous Air Pollutants (carbon oxides, nitrogen oxides, sulfur oxides).
Inorganic material: Material such as sand and other non-solubles.
Industrial waste: Material produced during manufacture requiring disposal out of the "system boundary."
Packaging material: Steel strapping, plastic lumber covers, cardboard corners, plastic or paper wrap.
Particulates: By-products of combustion or milling; can be solid or liquid state.
PM10: Standard for measuring solid and liquid particulates in suspension in the atmosphere; particulates are defined here as less than 10 micrometers in diameter.
Product: The primary material produced from manufacturing and "sold outside of the system boundary."
Recycled material: Material collected from the manufacturing facility operation that is re-used.
VOCs: Volatile Organic Compounds- produced in incomplete combustion of carbon based compounds; does not include methane; examples are oil based paints and gasoline fumes.

15 Appendix: Landfill Gas Equations

Equation 1: Where GHG_{DE} is GHGs directly emitted to atmosphere:

$$\begin{aligned} GHGDE \quad &= (W_{kg})(C)(C_{CO_2})(D)(1 - LFGC)(44/_{12}) \\ &+ (Wkg)(C)(C_{CH_4})(D)(1 - LFGC)(CH_4\text{GWP} * 16/_{12}) \end{aligned}$$

Equation 2: Where GHG_{LFGR} is GHG emitted from LFG energy recovery:

$$GHG_{LFGR} = (W_{kg})(C)(D)(LFG_C)(LFG_R)(44/_{12})$$

Equation 3: Where GHG_{LFGF} is GHG emitted from LFG flaring:

$$GHG_{LFGF} = (W_{kg})(C)(D)(LFG_C)(1 - LFG_R)(44/_{12})$$

Equation 4: EO_{LFGR} is the energy offset by LFG recovery:

$$EO_{LFGR} = \ (LFG_{HHV})(W_{kg})(C)(D)(LFGC \quad)(LFG_R\,)[(44/_{12})(C_{CO_2}) + (16/_{12})(C_{CH_4})$$

W_{kg}: Wood Mass in kg

C: Carbon Content of Wood = 0.53

D: Decomposition of Wood in Landfill = 0.23

C_{CO2}: Carbon content of wood converted to CO2 = 0.55

C_{CH4}: Carbon content of wood converted to CH4 = 0.45

CH_4GWP: Global Warming Potential of CH4 = 25

LFG_C: Landfill Gas Capture Efficiency = 75%

LFG_R: Landfill Gas Energy Recovery Efficiency = 70%

LFG_{HHV}: Landfill Gas Higher Heating Value = 15.8 MJ/kg