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Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking

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ABSTRACT

A cradle-to-grave life cycle assessment was done to identify the environmental impacts related to alkaline copper quaternary (ACQ)-treated lumber used for decking and to determine how the impacts compare to the primary alternative product, wood plastic composite (WPC) decking. A model of ACQ-treated lumber life cycle stages was created and used to calculate inputs and outputs during the lumber production, treating, use, and disposal stages. Lumber production data are based on published sources. Primary wood preservative treatment data were obtained by surveying wood treatment facilities in the United States. Product use and disposal inventory data are based on published data and professional judgment. Life cycle inventory inputs, outputs, and impact indicators for ACQ-treated lumber were quantified using functional units of 1000 board feet and per representative deck (assumed to be 320 square feet (30 square meters) of surface decking material) per year of use. In a similar manner, an inventory model was developed for the manufacture, use, and disposal of the primary alternative product, WPC. Impact indicator values, including greenhouse gas (GHG) emissions, fossil fuel use, water use, acidification, smog forming potential, ecological toxicity, and eutrophication were quantified for each of the two decking products. National normalization was done to compare the significance of a representative deck surface per year of use to a family's total annual impact footprint.

If an average U.S. family adds or replaces a deck surfaced with ACQ-treated lumber, their impact "footprint" for GHG emissions, fossil fuel use, acidification, smog forming potential, ecological toxicity, and eutrophication releases each is less than one-tenth of a percent of the family's annual impact. ACQ-treated lumber impacts were fourteen times less for fossil fuel use, almost three times less for GHG emissions, potential smog emissions, and water use, four times less for acidification, and almost half for ecological toxicity than those for WPC decking. Impacts were approximately equal for eutrophication.

1. Introduction

The environmental impacts of wood products used as building products have been the subject of research conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM). CORRIM's efforts build on a report issued under the auspices of the National Academy of Science regarding the energy consumption of renewable materials during production processes (Boyd et al., 1976). CORRIM's recent efforts have focused on an expanded list of environmental aspects and include the complete life cycle of wood products (Werner and Richter, 2007). Bowyer et al. (2004) provide life cycle inventory (LCI) data for northwest U.S. and southeast U.S. forest products producing regions, including structural products such as lumber. Other sources of LCI data focusing on untreated wood structural products include Johnson et al., 2005, Lippke et al., 2004, Milota et al., 2005, Perez-Garcia et al., 2005a,b, Price-Robinson 2004, Puettmann and Wilson 2005, Wilson 2006, and Winistorfer et al., 2005.

Untreated wood structural products are susceptible to degradation when left untreated (Ibach, 1999) in weather-exposed or wet environments subject to microbial or insect attack. To lengthen the service life of wood products susceptible to degradation, chemical preservation was introduced in the late 1700s and early 1800s. By 1842, wood preservation chemicals included mercuric chloride, copper sulphate, zinc chloride, ferrous sulphate with a sulphide, and creosote (Richardson, 1993). Over the years, industry has modified its wood preservation formulations with new preservatives, meeting consumer preferences and addressing various treated wood applications, such as railroad ties, utility poles, marine pilings, guard rail systems, highway bridge timbers, agricultural fencing,

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and dimensional lumber (including decking). Water-borne treatments, especially chromated copper arsenate (CCA), became the standard for weather-exposed residential and commercial lumber products during the latter half of the 1900s, because of the improvement in lumber life that the treatment provided.

In 2003, the wood preservative suppliers voluntarily modified label language for CCA preservative, limiting its application to heavy duty or industrial treated wood applications. As a result, demand for other non-chromated arsenical water-borne preservatives, such as alkaline copper quaternary (ACQ) and copper azole, expanded for residential and commercial lumber applications. Preservatives use copper because it exhibits good biocidal activity against fungi and some insects (Nicholas and Schultz, 1997). ACQ is a water-borne preservative utilizing copper and quaternary ammonium compound (quat). The American Wood Protection Association (AWPA 2010a) specifies ACQ-treated lumber as appropriate for use in sawn wood product applications including above-ground, interior construction (dry and damp), above-ground, exterior construction, and ground contact. ACQ is one of the preservatives used to improve the service life of decking products susceptible to decay by insect and microbial attack.

An alternative to treated lumber decking is wood plastic composites (WPC). WPC is produced by many manufacturers using differing formulas and manufacturing processes. The first uses of WPC as decking were in the early 1990s (Youngquist, 1995). Generally, WPC manufactured for the U.S. market is composed of thermoplastics and wood flour, although proportioned amounts and additional fillers vary considerably between specific products (Clemons, 2002). The WPC product has approximately the same dimensions as, and is generally used interchangeably with, ACQ-treated lumber for decking surfaces. Typically, WPC decking is installed over a framework of treated lumber, since WPC does not have the material properties needed for use as joists, posts, or ledgers.

2. Goal and scope

This study investigates the cradle-to-grave life cycle environmental impacts related to ACQ-treated lumber decking and uses life cycle assessment (LCA) to quantify such impacts. It covers one treated wood product in a series of LCAs commissioned by the Treated Wood Council (TWC). The series of LCAs also covers borate-treated lumber, creosote-treated railroad ties, pentachlorophenol-treated utility poles, CCA-treated marine pilings, and CCA-treated guard rail systems.

This study inventories the environmental inputs and outputs attributable to ACQ-treated lumber decking, completes a comparable inventory of WPC decking, and calculates and makes comparisons of the product's impact indicators. The scope covers the cradle-to-grave life cycle of ACQ-treated lumber and WPC decking.

A baseline water-borne wood treatment used to preserve lumber decking material was chosen for the purpose of conducting the study. The baseline preservative provides the user a tool with which to evaluate common treated lumber products and make comparisons with the primary alternative material.

This study was performed using LCA methodologies in a manner consistent with the principles and guidance provided by the International Organization for Standardization (ISO, 2006a,b) in standards ISO 14040 and 14044. The study includes the four phases of an LCA: 1) Goal and scope definition; 2) Inventory analysis; 3) Impact assessment; and 4) Interpretation. LCA has been recognized as the tool of choice for evaluating environmental impacts of a product from cradle-to-grave, and determining the environmental benefits one product might have over its alternative (Andersson et al., 1998). The environmental impacts of ACQ-treated lumber and WPC decking are assessed throughout their life cycles, from the extraction of the raw materials through processing, transport, use as decking, reuse, and recycling or disposal of the product.

3. Life scycle inventory analysis

The inventory phase of the LCA developed the input flows from, and output flows to, the environment through each life cycle stage of the product. Inventory development included defining the products, selecting a means to compile data, obtaining and developing applicable life cycle data for life stages, distributing flows appropriately between the target and co- or by-products, and summarizing the flow data. The cradle-to-grave life cycle system boundary considered in this LCA is illustrated in Fig. 1.

Life cycle input and output flows were quantified using functional units of 1000 board feet (Mbf) and per representative deck surface per year of use. The board-foot (bf) functional unit is a standard unit of measure for the U.S. lumber industry and is equivalent to sawn lumber nominally one foot (0.31 m) long, one inch thick, and 12 inches wide. A one-foot long, nominal 2×6 inch (51×152-mm) piece of board contains one board-foot. The representative deck is assumed to be 16 feet (4.9 m) by 20 feet (6.1 m) and equal to 320 square feet (30 square meters) of surface decking material. The use of the representative deck functional unit considers volume variances between ACQ-treated lumber and WPC and allows for comparison based on the coverage of the product on the decking surface. Use of the functional unit can be extrapolated to national treated lumber or alternate product use.

3.1. ACQ lumber deck inventory

The product of primary focus in the LCA was ACQ Type D-treated Southeastern species, $5/4 \times 6$ inch (32×152 mm) nominal dimensional lumber (also referred to as "radius-edge decking"), treated for above-ground, exterior exposure according to the AWPA standards (AWPA 2010a) for use category UC3B (exterior exposure, above-ground). Radius edge decking is typically specified for the deck surface and rail cap. For the purpose of understanding unit processes that contribute to the environmental impacts of ACQ-treated lumber, four main life cycle stages were recognized, including:

- Lumber production stage;
- Lumber treating stage;
- ACQ-treated lumber service life as decking stage; and
- ACQ-treated lumber disposal stage.

This study builds on existing CORRIM research for lumber products and adds the treating, use, and disposal stages of ACQ-treated lumber. For the lumber production stage, the main sources of forest products LCI data were Milota et al. (2005) and Johnson et al. (2005). The data are available through the U.S. Department of Energy National Renewable Energy Laboratory (NREL, 2008a) U.S. LCI Database. Specifically, the database for planed and dried Southeastern lumber production was selected. The dominant species is Southern pine. The data cover production of wood grown on Southeastern U.S. forest land at average forestry intensity, milled to dimensions, kiln-dried, and planed at the lumber mills (NREL 2008a). These data are representative of lumber shipped to U.S. wood-preserving plants for treatment. Processes including inputs and outputs related to burning wood biomass to dry lumber, use of electricity in saw mills, and transportation-related inputs and outputs were apportioned per functional unit. In this manner, the amounts of electricity, wood fuel, and transport ton-miles required for each Mbf, also referred to as 1.0 Mbf of lumber, were calculated.

The lumber treatment stage includes the manufacture of the ACQ preservative and the treatment of lumber with ACQ

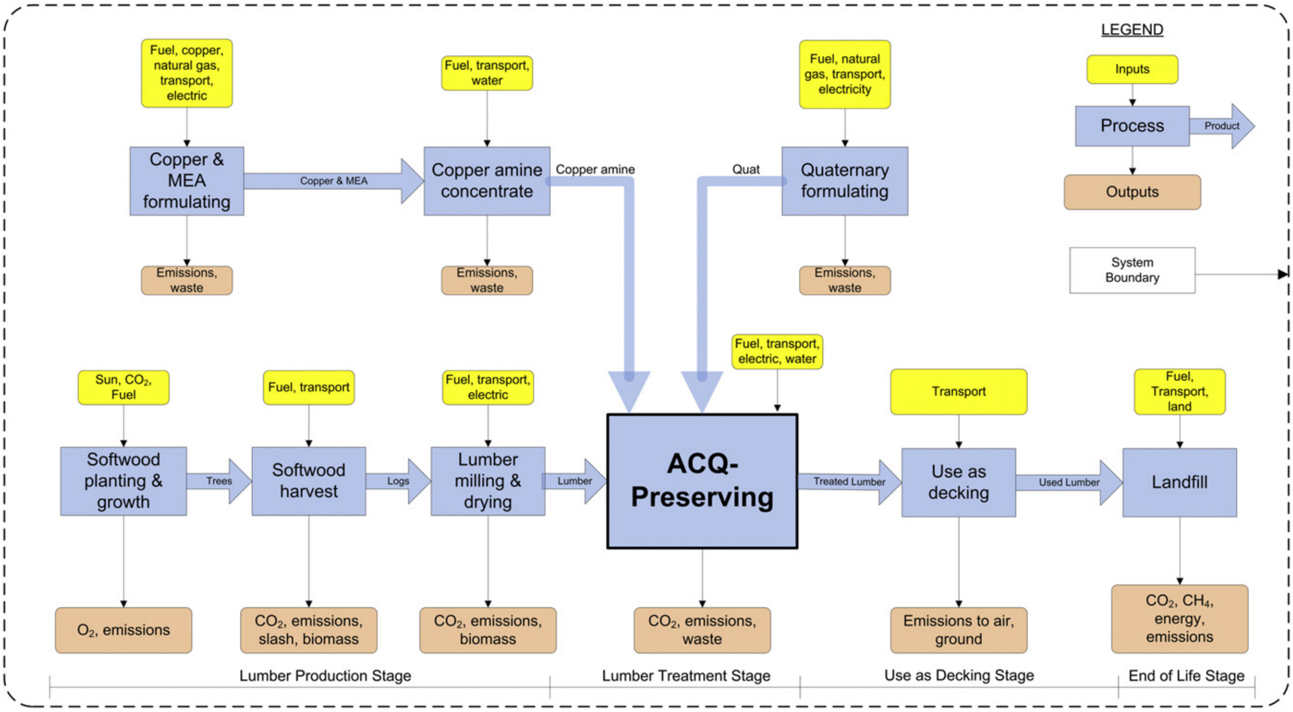

Fig. 1. Life cycle diagram of ACQ-treated lumber.

preservative. AWPA (2010b) standard P5-09 specifies ACQ retentions of 0.15 pounds per cubic foot (pcf) (2.4 kg m^{-3}) for above-ground sawn products with exterior exposure. The general composition of ACQ-D, as stated in AWPA P5-09, Section 14, includes 66.7% copper as copper oxide and 33.3% quat as didecyl dimethyl ammonium chloride (DDAC). The copper component is dissolved in ethanolamine at 2.75 parts ethanolamine, by weight, for each part copper oxide (AWPA 2010b). The quat is shipped separately and mixed as part of the treating process.

Inputs and outputs for ACQ-D production include the weighted totals of the basic components of copper, quaternary, and ethanolamine. The relative weights of components were calculated for each pound of ACQ used in wood treatment. Although defined as one pound of ACQ, the formulation actually includes 0.667 lbs (0.303 kg) of copper oxide, 0.333 lbs (0.151 kg) of quat, and 1.83 pounds (0.0.830 kg) of ethanolamine. Published life cycle inventory data were not available for ACQ component production and a survey of ACQ manufacturers was not done for reasons of confidentiality; however, components (such as copper, quaternary, and monoethanolamine) necessary for the manufacture of ACQ were inventoried and modeled using literature sources for copper LCI data (Life Cycle Centre, 2009 and Ayres et al., 2002) and analogous component processes available through NREL. The data were used to complete the LCI for ACQ production.

Primary input and output data for the wood-preserving process were collected from ACQ-treating plants. Data from fifteen returned questionnaires (thirteen from southeastern and two from western U.S. states) were used as inventory inputs and outputs. The southern treaters accounted for 97% of the surveyed ACQ-treated lumber volume. The total volume of lumber treated with ACQ by treater survey reporting plants is approximately 662,000 Mbf in 2007. The total estimated amount of dimensional lumber (4.7 million Mbf), radius-edge heavy decking (0.74 million Mbf), and boards (0.22 million Mbf) treated with water-borne preservative in the U.S. in 2007 is 5.7 million Mbf (Vlosky, 2009). Of the 5.7 million Mbf, Vlosky estimates 25% or 1.4 million Mbf were treated with ACQ. Thus, the treater survey covers approximately 47% of the 2007 ACQ-treating market. Weighted average production data, such as water, electricity and fuel use, and transportation inputs, were calculated per Mbf from the treater survey results and used as inputs in the treating stage inventory.

The ACQ-treated lumber use stage included transportation of lumber to the use site, installation of decking, maintenance during its use life, releases during life, and demolition at the end of use. Use of deck sealer was included and modeled as a U.S. average of one sealer application over the deck life of 10 years, acknowledging that many decks are never sealed and many decks are sealed more than once. The representative sealer was assumed to consist of 25% volatile organic compounds (VOCs), 25% water, and 50% solids. The manufacture of deck sealer was modeled using an analogous process (polyethylene terephthalate (PET)), and using database information available from NREL (2008b). The VOC portion of the sealer was assumed to evaporate as an air emission during the use stage. Deck sealer was modeled as if applied one time during the deck life.

Decks are commonly replaced for aesthetic reasons well before structural failure. An average use life assumption of 10 years (Smith, 2005) was applied, acknowledging that safe service life could be much longer. At the end of use, decks were modeled as if demolished and 100% of ACQ-treated lumber disposed in a solid waste landfill.

The disposal stage includes landfill construction inputs, transportation requirements, and releases. The disposal stage model was created based on an LCA of solid waste management (USEPA 2006a). ACQ-treated lumber decking was modeled assuming disposal in both wet (bioreactor) and dry municipal waste landfills and construction and demolition waste landfills. The disposal model results in 77% of the wood carbon being sequestered, 17% released as carbon dioxide, and 6% released as methane. A portion of the methane is assumed to be collected. Methane capture efficiencies depend on the landfill type and have been estimated using professional judgment. Of the captured methane, a portion is assumed to be used to generate electricity and the remainder is assumed to be destroyed by combustion (flaring), so that all the recovered methane is converted to carbon dioxide. The landfill stage considered for this LCA includes 100 years of product life in the landfill after disposal. This time frame was chosen to allow the primary phase of anaerobic degradation to take place (i.e., primary generation of methane is completed in the 100-year time frame). Inputs and outputs related to landfill construction and closure (Mènard et al., 2003) were apportioned on a mass disposed basis.

Transportation-related inputs and outputs were included in each life cycle stage. Distances and transport modes for preservative supply to treaters, inbound untreated and outbound treated wood were based on treater survey weighted averages. Other material transport distances and modes were based on professional judgment. Inputs and outputs (per ton-mile) resulting from transportation modes were based on NREL U.S. LCI database information.

3.2. WPC inventory

In order to support comparison of products through their complete life cycles, an LCA was completed for WPC. A "typical" WPC product design has been assumed to be representative of the general product category. For the WPC LCA, a reference material was chosen with nominal dimension of $5/4 \times 6$ inch (32×152 mm) and actual dimensions of 1.175×5.40 inches (29.84×137 mm). The spacing on a typical deck is one decking plank every 6 inches (152 mm), the same assumption used for ACQ-treated lumber decking. Some WPC has void sections in cross-section to reduce the material used in manufacturing and reduce product weight. Void space is minimal with 5/4 inch WPC and is considered in a sensitivity analysis.

The representative WPC product includes a mixture of recycled wood fiber and recycled and virgin high-density polyethylene (HDPE). This representative product does not infer that virgin and recycled plastics are mixed in the same manufacturing process. The WPC product has approximately the same dimensions and can be used interchangeably with ACQ-treated lumber for decking. Published data were used and assumptions made to complete the LCA for the cradle-to-grave life cycle of WPC. A survey of WPC manufacturers was not done. Inputs such as fuel use, water use, and solid waste generation at the WPC manufacturing facility were estimated.

The general category of WPC covers a wide and evolving variety of products. The plastic content may vary from as little as approximately 30% by weight to as much as 100%, and may be derived entirely from post-consumer use recycled material to 100% virgin plastic (Platt et al., 2005). For this LCA, WPC was modeled as if manufactured from 50% recycled wood flour, 25% post-consumer recycled HDPE, and 25% virgin HDPE. Although formulas vary, this mixture was assumed as the U.S. national average. The main sources of HDPE LCI data were the U.S. LCI database made available by NREL (2008c) and from Franklin Associates (2007). Inventory input and output for post-consumer recycled HDPE use, covering collection, sorting, reprocessing, and reject disposal, were based on an LCA of plastic recycling (Arena et al., 2003). Preservatives, such as borates, are added by some WPC manufacturers to the wood portion to retard decay, but preservative addition is not included in this LCA.

As with treated wood, the WPC deck life span often is shorter than the potential product use life because owners replace decks as part of overall renovation projects related to changing needs or desires or for aesthetic reasons. While WPC manufacturer literature often claims longer use life than obtained from treated lumber, it is noted that the same factors of surface weathering, stains, and the desire to upgrade deck designs apply to WPC. As a result, many WPC decks are expected to be replaced prior to the full useful product life. The LCI of WPC assumes a use life of 10 years and includes no maintenance sealer applications. Chemical cleaners used on WPC decking to remove staining and mold were considered outside the scope for inclusion in the LCA of WPC.

Fasteners and installation equipment are essentially the same for both ACQ-treated lumber and WPC and were not considered in the inventory. Furthermore, structural framing, such as posts, joists, and ledgers can vary, but generally are approximately the same for $5/4 \times 6$ inch ACQ-treated lumber decking or a comparable WPC decking product and were not addressed in the LCA.

A summary of selected inventory inputs and outputs for ACQ-treated lumber and WPC decking is shown in Table 1.

4. Life cycle impact assessment

4.1. Selection of the impact indicators

The impact assessment phase of the LCA uses the inventory results to calculate indicators of potential impacts of interest. The environmental impact indicators are considered at "mid-point" rather than at "end-point" in that, for example, the amount of greenhouse gas (GHG) emission in pounds of carbon dioxide equivalent (CO_2-eq) was provided rather than estimating end-points of global temperature or sea level increases. The life cycle impact assessment was performed using USEPA's (2009) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2009) to assess GHG, acidification, ecological toxicity, eutrophication, and smog emissions. Other indicators also were tracked, such as fossil fuel use and water use.

4.1.1. GHG emissions

Emissions of the GHGs – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – were multiplied by their respective global warming potential equivalence factors (TRACI 2009) of 1, 21, and 296, respectively, to calculate pounds CO_2-equivalent emissions per unit of product (i.e., Mbf or 320 sf of deck per year of use). The intent of the GHG impact indicator is to quantify human-caused (anthropogenic) emissions that have the potential to affect global climate. Although carbon dioxide molecules behave the same, whether from fossil fuels or biomass, they are addressed differently in calculating GHG emissions. Carbon dioxide resulting from burning or decay of wood grown on a sustainable basis is considered to mimic the closed loop of the natural carbon cycle (USEPA 2009) and is not included in the calculation of GHGs. However, methane that results from the decay of wood or other carbon-based waste in landfills is counted. This methane is produced because disposal in engineered landfills results in anaerobic decay instead of combustion or surface (aerobic) decay.

4.1.2. Resource depletion (fossil fuel use)

The chosen impact indicator for assessment of resource depletion was fossil fuel use. Fossil fuel use currently is an issue related to global climate change (as a non-renewable source of CO_2 emissions), national security (dependency on imports), and national and personal finances (diminishing resources result in increased costs and limited availability). The selected impact indicator unit of measure was total million BTU (MMBTU) of fossil fuels used.

4.1.3. Acidification

The acidification impact indicator assesses the potential for emissions to air that result in acid rain deposition on the Earth's surface. Factors relating to the relative potential of released chemicals to form acids in the atmosphere (TRACI 2009) were multiplied by the chemical release amounts to calculate equivalent acid rain potential as hydrogen ion (H^+) mole equivalents.

Table 1
Cradle-to-grave inventory summary for ACQ-treated lumber and WPC.

Infrastructure Processes	Units	ACQ-Treated Lumber Life		WPC Decking Life	
		Per Mbf	Per representative deck per year of use[a]	Per Mbf	Per representative deck per year of use[a]
Inputs from technosphere					
Electricity, at grid, US	kWh	417	17	1718	69
Natural gas, processed, at plant (feedstock)	ft3	641	26	19,087	763
Natural gas, combusted in industrial boiler	ft3	135	5.4	8348	334
Diesel, combusted in industrial boiler	gal	5.9	0.2	42	1.7
Liquefied petroleum gas, combusted in industrial boiler	gal	0.15	0.0059	0.0049	0.00019
Residual fuel oil, combusted in industrial boiler	gal	0.081	0.0033	1.2	0.049
Diesel, combusted in industrial equipment	gal	1.6	0.065	0	0
Gasoline, combusted in industrial equipment	gal	0.15	0.0058	0.22	0.0086
Hogfuel/biomass (50%MC) for heat energy	lb	849	34	46	1.8
Coal-bituminous & sub., combusted in industrial boiler	lb	0.097	0.0039	0.46	0.019
Truck transport, diesel powered	ton-miles	476	19	3785	151
Rail transport, diesel powered	ton-miles	84	3.4	316	13
Barge transport, res. oil powered	ton-miles	2.7	0.11	57	2.3
Ship transport, res. oil powered	ton-miles	32	1.3	51	2.0
Energy (unspecified)	MJ	2.8	0.11	0	0
Petroleum refining coproduct, unspecified, at refinery	lb	0	0	254	10
Lumber-dry, planed	bf	1000	40	0	0
Wood fiber by-product	lb	0	0	2710	108
Landfill capacity	ton	1.1	0.044	2.2	0.087
Inputs from nature					
Water	gal	308	12	848	34
Bark from harvest	ft3	5.3	0.21	0	0
Unprocessed coal	lb	246	9.8	948	38
Processed uranium	lb	0.00065	0.000026	0.0024	0.000097
Unprocessed crude oil	gal	5.1	0.20	3.6	0.14
Unprocessed natural gas	ft3	1043	42	39,723	1589
Biomass/wood energy	Btu	0	0	0	0
Hydropower	Btu	114,688	4588	445,138	17,806
Other renewable energy	Btu	13,156	526	33,132	1325
Carbon (from air)	lb	295	12	825	33
Outputs to nature (air, except where noted)					
CO_2-fossil	lb	1116	45	4957	198
CO_2-non-fossil	lb	−544	−22	920	37
Carbon monoxide	lb	3.7	0.15	3.5	0.14
Ammonia	lb	1.815	0.073	0.0032	0.00013
Hydrochloric acid	lb	0.22	0.0089	0.57	0.023
Hydrofluoric acid	lb	0.020	0.00080	0.071	0.0028
Nitrogen oxides (NOx)	lb	2.5	0.10	8.5	0.34
Nitrous oxide (N_2O)	lb	0.032	0.0013	0.026	0.0010
Nitric oxide (NO)	lb	0.050	0.0020	0	0
Sulfur dioxide	lb	5.7	0.23	44	1.8
Sulfur oxides	lb	0.53	0.021	0.55	0.022
Particulates (PM_{10})	lb	3.3	0.13	0.41	0.016
Volatile organic compounds	lb	2.1	0.083	1.9	0.075
Methane	lb	82	3.3	157	6.3
Acrolein	lb	0.015	0.00061	0.00014	0.0000055
Arsenic	lb	0.00014	0.0000056	0.00020	0.0000081
Cadmium	lb	0.000025	0.0000010	0.000039	0.0000016
Lead	lb	0.00024	0.0000098	0.00021	0.0000086
Mercury	lb	0.000026	0.0000010	0.000044	0.0000018
Copper (to water)	lb	0.00033	0.000013	0	0
Copper (to soil)	lb	4.7	0.19	0	0
Solid wastes-landfill	lb	90	3.6	4463	179
Solid wastes-recycled	lb	0.025	0.0010	0	0
Wood wastes-treated-landfill	lb	2132	85	0	0

[a] Functional unit is inventory item per representative deck surface (320 square feet) per year of service life, assuming a 10-year deck surface service life. Shorter service life will increase inventory values. Longer service life will decrease inventory values.

4.1.4. *Water use*

The total amount of water used in each unit process of the product life was calculated in gallons. Since water use data were not available for all supporting process units, most importantly for electricity production, results for this impact category may be of limited value.

4.1.5. *Ecological toxicity*

The ecotoxicity impact category includes ecologically toxic impact indicators that are normalized to a common herbicide of accepted ecological toxicity, 2,4-D (2,4-Dichlorophenoxyacetic acid). The amounts of constituents released to air during product life cycle stages are multiplied by the factors contained in TRACI (2009) to calculate the indicator values.

4.1.6. *Eutrophication*

The eutrophication impact indicator was normalized to pounds of nitrogen equivalent. The factors contained in TRACI (2009) were used to calculate the indicator values in pounds of nitrogen equivalents. Eutrophication characterizes the potential impairment

Table 2
ACQ-treated lumber environmental impacts per 1.0 Mbf and by life cycle stage.

Impact Indicator	Units	Life Cycle Stage				ACQ lumber cradle-to-grave
		Lumber production	Treating	Use	Disposal	
GHG Emissions	lb-CO_2-eq	235	174	240	2203	2853
Fossil Fuel Use	MMBTU	1.4	1.6	1.3	1.7	5.9
Acid Rain Potential	H^+ moles-eq	118	110	186	189	604
Water Use	gal	187	121	0	0	308
Smog Potential	g-NOx-eq/m	1.7	0.41	0.21	0.45	2.7
Eutrophication	lb-N-eq	0.057	0.086	0.18	0.010	0.33
Ecological Impact	lb-2,4-D-eq	3.9	0.18	0.39	1.9	6.4

Notes:Lumber production includes: replanting a harvested area of forest, growing and maintaining the forest plantation until harvest, harvesting of the trees, drying, and milling and associated transportation.Treating includes: preservative manufacture, treatment, storage of untreated and treated lumber, releases, and transportation of lumber and preservatives to the plant.Use includes: transportation of lumber to the installation site, install, maintenance, releases, and demolition.Disposal includes: impacts of landfill construction, disposal, and associated transportation.Cradle-to-grave is the sum of lumber production, treating, use, and disposal.

of water bodies (such as algal blooms and use of dissolved oxygen) resulting from emission to the air of phosphorus, mono-nitrogen oxides (NOx), nitrogen oxide, nitric oxide, and ammonia.

4.1.7. *Smog forming potential*

The smog impact indicator assesses the potential of air emissions to result in smog. The factors contained in TRACI (2009) were used to calculate the indicator values. Smog emissions result in decreased visibility, eye irritation, respiratory tract and lung irritation, and vegetation damage (USEPA 2006b). Factors relative to smog forming emissions were multiplied by the TRACI (2009) factors and reported in grams of NOx equivalents per meter.

4.2. *Impact indicators considered but not presented*

The TRACI (2009) model, a product of USEPA, and the USEtox model, a product of the Life Cycle Initiative (a joint program of the United Nations Environmental Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC)), offer several additional impact indicators that were considered during the development of the LCA including human health, and ecological impacts due to releases to soil and water. The decision was made not to include these impact indicators because of insufficient data or concerns regarding misinterpretation. Thus, the life cycle releases of chemicals associated with products likely of interest for human health and land and water ecological impacts are reported in the Table 1 inventory, but impact indicators for these categories are not addressed. Land use impacts were beyond the scope of this LCA.

4.3. *Total energy*

The total amount of energy input to a product over its life cycle is not considered an impact indicator, but was tracked in the LCA. Total energy is the energy derived from all sources, including fossil, biogenic, and grid electricity converted to common units of millions of BTU (MMBTU) per unit. Energy sources are, to varying degrees, fungible, meaning they can be transferred from one use to another. For example wood fuel (biomass) can, as in the case of lumber, be used to fuel dry kilns, as home heating pellets, or fuel for electric power generation. Similarly, kilns could be heated with natural gas. Generally, products that require less input of energy will have less environmental impact. Tracking total energy and the proportions as biogenic versus fossil allows users to compare this aspect of each product.

5. Life cycle interpretation

5.1. *Findings*

To assess the processes that result in environmental impact from ACQ-treated lumber, impact indicator values were totaled at the four life cycle stages. The impact indicator values at each of the four life cycle stages, and a total for the cradle-to-grave life cycle of ACQ-treated lumber, are reported in Table 2.

Normalization was included in the LCA to support comparisons between products and to identify significance of impacts. Impact indicator values are normalized to a “representative” size deck surface per year of use (indicator value/deck surface/year). The volume of 5/4 $\times$ 6 inch lumber needed for this deck surface is equivalent to 0.40 Mbf. ACQ-treated lumber inventory data and environmental data were totaled at the four life cycle stages; however one-to-one comparisons to WPC were made only at the use and disposal stages. Impact indicator values, normalized per deck per year for ACQ-treated and WPC decking, are shown in Table 3.

To allow relative comparison of indicators between products, impact indicator values were normalized to cradle-to-grave ACQ-treated lumber values of one (1.0), with the WPC impact indicator values being a multiple of one (if larger) or a fraction of one (if smaller). The normalized results of Table 3 are shown graphically in Fig. 2 to visually illustrate the comparative assertions about the life-cycle impacts of ACQ-treated lumber and WPC decking.

Fig. 2 illustrates that there are impact differences between the products, but is not intended to explain the significance of a family’s decision to add or replace a deck. National normalization provides comparison of the product values as a percentage of national average impacts for U.S. families (Bare et al., 2006). Annual

Table 3
Comparison of environmental impact of a representative deck per year of use.

Impact Indicator	Units	ACQ-treated lumber use as decking	ACQ-treated lumber in landfill	WPC use as decking	WPC decking in landfill
GHG Emissions	lb-CO_2-eq/yr	26	114	163	330
Fossil Fuel Use	MMBTU/yr	0.17	0.24	3.2	3.4
Acid Rain Potential	H^+ moles-eq/yr	17	24	90	105
Water Use	gal/yr	12	12	34	34
Smog Potential	g−NOx-eq/m/yr	0.091	0.11	0.25	0.28
Eutrophication	lb-N-eq/yr	0.013	0.013	0.014	0.015
Ecological Impact	lb-2,4-D-eq	0.18	0.25	0.28	0.43

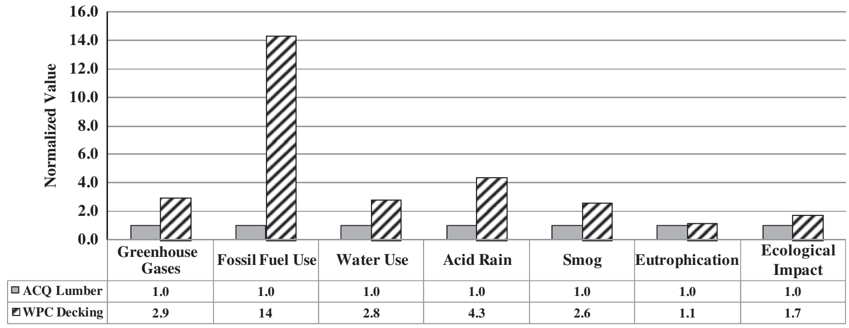

Fig. 2. Cradle-to-grave impact indicator comparison of a representative U.S. family deck of 320 square feet (29.7 square meters) (normalized to ACQ-treated lumber = 1.0).

energy use was compiled from values in U.S. Department of Energy's Annual Review 2007 (EIA 2008). For example, fossil fuel use resulting from the addition or replacement of a representative ACQ-treated lumber deck surface is 0.24 MMBTU per deck surface per year, which represents 0.028% of an average family's annual fossil fuel use. Impact indicator values, normalized to national average family (3 persons) impacts (shown in Table 4), are provided to add a measure of significance to the products. From Fig. 2 and Table 4, one can observe, for example, that total life cycle emissions of GHGs are approximately three times more for WPC than for ACQ-treated deck lumber. For ACQ, the representative deck surface accounts for 0.074% of a family's annual GHG impact. The representative WPC deck surface accounts for 0.21% of a family's annual GHG impact.

The life cycle of ACQ-treated lumber requires the use of both fossil and biomass sources of energy. Together, the fossil and biomass energy result in a total energy requirement. Much of the fossil fuel energy needed during the life cycle of ACQ-treated lumber used for a deck's surface is attributed to application of sealer during the deck use life and landfill construction and closure. Much of the biomass energy use attributable to ACQ-treated lumber is a result of biomass use at saw mills as a substitute for fossil energy. Energy requirements for WPC are mostly from fossil fuel sources. A summary of biomass and fossil energy and their contribution to total energy is shown in Table 5.

5.2. *Data quality analyses*

Data quality analysis per ISO 14044 (ISO 2006b), Section 4.4.4, included a gravity analysis, uncertainty analysis, and sensitivity analysis.

5.2.1. *Gravity analysis*

Table 6 shows the contribution to each indicator made by each life stage of the products. Life stage impacts that are notably large (higher gravity) compared to other life stages are indicated in **bold** print. For ACQ-treated lumber decking, assessed at four life cycle stages, values greater than or equal to 30% are noted. For WPC, assessed at two life cycle stages, values greater than 60% are noted.

Table 4
Impact indicators as percent of U.S. family impact.

Impact Indicator	Units	ACQ-Treated Lumber	WPC Decking
GHG Emissions	lb-CO_2-eq/yr/family	0.074%	0.21%
Fossil Fuel Use	MMBTU/yr/family	0.028%	0.39%
Acid Rain Potential	H+ mole-eq/yr/family	0.049%	0.21%
Water Use	gal/yr/family	0.00091%	0.0025%
Smog Potential	g−NOx-eq/m/yr/family	0.024%	0.063%
Eutrophication	lb-N-eq/yr/family	0.039%	0.044%
Ecological Impact	lb-2,4-D-eq/yr	0.053%	0.089%

5.2.2. *Uncertainty analysis*

As a cradle-to-grave LCA, many data inputs involve uncertainty. Some assumptions were based only on professional judgment. Copper released during ACQ lumber treatment, storage, use as decking, and finally in landfills can only be estimated by use of assumptions. The uncertainty of these assumptions is large because of variations in production facility containment structure integrity, production facility housekeeping practices, regional location of the treating facility and use site (i.e., precipitation amount will directly impact leaching), and disposal site characteristics. Since copper is not released to air, the impact indicators assessed do not change with increases or decreases in amounts of copper released.

Deck sealers were assumed to be applied in the use stage of the ACQ-treated lumber's life cycle. A representative sealer was chosen for modeling in the LCA. All VOCs associated with the sealer are assumed to be emitted to the air when the sealer is applied. The remaining sealer is assumed to be a combination of carbon-based solids that partially oxidize during use and partially remain with the wood to disposal. Sealer manufacturer formulation variances and assumptions used in the environmental fate model result in uncertainty.

Landfill fate and release models are based on USEPA data (2009) used to estimate GHG emission for its inventory, and modeled assumptions result in variability of impact indicator values, especially GHG. As more landfills in the U.S. install methane collection systems and increase methane recovery efficiencies, methane emissions from landfills will decrease. Further, in the LCA, ACQ-treated lumber is assumed to degrade to the same degree and at the same rate as round untreated wood limbs disposed in a landfill. If treatment retards or prevents degradation of the wood in a landfill, then releases of methane could occur over a longer period, reducing the rate per time unit. Because of the landfill uncertainties, further analysis was conducted as part of the sensitivity analysis.

5.2.3. *Sensitivity analysis*

Sensitivity analysis was completed to determine the effects of assumption changes on LCA results. The authors strived to make realistic assumptions in all cases. Some assumptions used for the WPC LCA are based only on professional judgment and no survey of WPC manufacturers was done. Areas of uncertainty most likely to impact the results, such as percentage of the WPC product consisting of virgin and/or recycled HDPE, were addressed with sensitivity analysis.

5.2.3.1. ACQ preservative retentions. ACQ retention in lumber products was adjusted, as low retention and high retention scenarios. The baseline treatment retention used in the assessment was 0.15 pcf (2.4 kg m^{-3}). Two cases were modeled for sensitivity, including: 1) low retention at 0.10 pcf (1.6 kg m^{-3}), and 2) high retention at 0.40 pcf (6.4 kg m^{-3}). Since production of ACQ is energy

Table 5
Energy sources by product and stage.

Product and Life Cycle Stage	Total Energy Input MMBTU	Fossil Fuel Use MMBTU	Biomass Energy MMBTU	Fossil Fuel Intensity % of total	Biomass Intensity % of total
ACQ lumber production and use	0.33	0.17	0.153	51%	47%
ACQ lumber cradle-to-grave	0.41	0.24	0.154	58%	38%
WPC decking production and use	3.2	3.2	0.005	99%	0.2%
WPC decking cradle-to-grave	3.4	3.4	0.008	98%	0.2%

Note: Intensity percentages do not always add to 100% because of non-fossil, non-biomass and energy recovery (recycling) contributions.

and fossil fuel intensive, increasing the ACQ content from 0.15 to 0.40 pcf results in increases in GHG (5%), fossil fuel use (25%), acidification (56%), ecological toxicity (2%), and smog (2%). Eutrophication is most dramatically impacted at an increase of 111%.

5.2.3.2. Lumbar thickness. As Lumber a baseline case, the model assumes 100% of all ACQ-treated lumber decks are constructed with 5/4 inch × 6 inch (32 × 152 mm) nominal dimensional lumber. For the sensitivity test, a case assuming 20% 5/4 inch × 6 inch with 80% 2 × 6 inch (51 × 152 mm) nominal lumber was modeled. Changing from 100% to 20% 5/4 inch board material and to 80% 2 inch material for decking means more wood volume is required for the same surface area. Thus, all inputs and outputs and resulting impact indicators are increased proportionally between 30 and 40% over the baseline model results.

5.2.3.3. Sealer application Frequency. If three sealer applications are made in the ten-year life (once every three years), then some impact indicators are increased: GHG (16%), fossil fuel use (42%), acid rain (19%), eutrophication (8%), ecotoxicity (13%) and smog (14%). However, these increases do not change the comparative ranking when compared to WPC. Furthermore, although WPC manufacturers recommend using cleansing products on WPC, these products have not been considered in the LCA of WPC.

5.2.3.4. Landfill decay models. Barlaz (1998) reported that approximately 77% of the carbon in wood fiber of branches disposed in landfills is sequestered after primary decomposition has occurred. This estimate of carbon sequestration was used in the landfill model. The presence of lignin (a major carbon-based component of wood) can interfere greatly with cellulose and hemicellulose degradation under the anaerobic conditions of landfills. Laboratory research shows it to be very resistant to decay in landfills because cellulose and hemicellulose are embedded in a matrix of lignin (Ham et al., 1993a,b; Wang et al., 1994). Preservative in disposed ACQ-treated lumber is expected to further increase carbon sequestration by retarding decay, but is not included in the baseline assumptions. To demonstrate the sensitivity of carbon sequestration, a test case was assessed where 90% wood fiber carbon sequestration occurred in the landfill. Based on the results of this modeling, increased sequestration of 90% results in reduced GHG emissions (34%) when compared to the baseline model. However, increases to other impact indicator values result from reduced methane production and in-turn reduced methane collection and use to off-set fossil fuel use.

5.2.3.5. WPC manufacturing variables. WPC was considered to be without voids (i.e., solid in cross-section). A sensitivity analysis was done to assess the impact to indicators when incorporating voids in the WPC. Incorporating voids in WPC decreases all impact indicators by the percent void space incorporated into the WPC product. However, it is noted that the incorporation of voids will require additional electricity use in the manufacturing stage, because of increased extrusion friction.

5.2.3.6. Recycled HDPE vs. virgin HDPE. The fraction of HDPE derived from post-consumer recycled content impacts the LCA results for WPC. Sensitivity analysis shows that WPC, manufactured with post-consumer HDPE, has lower impact than when manufactured with virgin HDPE. However, this best case scenario for WPC does not change the overall comparative results (i.e., ACQ-treated lumber continues to have lower impact for the cradle-to-grave life cycle). If 100% post-consumer HDPE material is used instead of 50%, fossil fuel use decreases from 14 to 4.4 times the value of ACQ-treated lumber and total energy decreases from 8.5 to 2.8 times the value of ACQ-treated lumber.

5.2.3.7. WPC deck life. Extending the use life of WPC decks reduces impacts in reverse proportion to the life extension. Doubling the deck life cuts annual impacts in half. Since WPC has been shown to be subject to weathering and decay (Laks et al., 2008 and Morrell et al., 2006), the assumption of such life extension does not seem reasonable with current designs.

5.3. Limitations

The scope of the study was limited to boundaries established in the Goal and Scope document prepared for this LCA. Limitations included reliance on published or publically available information in many instances. Such information was assumed to be accurate. Value judgments such as purchase price and ease of installation were beyond the scope of this LCA.

The life cycle inventory completed for WPC was designed to represent the typical or average product on the market, and

Table 6
Impact indicator contributions by life stage (percent of cradle-to-grave life impact per product).

Impact Indicator	ACQ-Treated Lumber					WPC	
	Lumber production stage	Treating stage	Use stage	Lumber production, treatment, and use stages	Disposal stage	Production and use stages	Disposal stage
GHG	8%	6%	8%	22%	**78%**	49%	51%
Fossil Fuel Use	23%	26%	22%	71%	29%	**94%**	6%
Acid Rain Potential	20%	18%	**31%**	69%	**31%**	**86%**	14%
Water Use	**61%**	**39%**	0%	100%	0%	**100%**	0%
Smog Potential	**61%**	15%	8%	84%	16%	**87%**	13%
Eutrophication	18%	26%	**53%**	97%	3%	**95%**	5%
Ecological Impact	**61%**	3%	6%	70%	**30%**	**65%**	35%

therefore by design, likely will not be accurate for a specific product in this category. A survey of manufacturers of WPC was not done; therefore, inputs such as fuel use, water use, and solid waste generation at the WPC manufacturing facility are estimated using professional judgment and confidential sources of information. Inventory data on the manufacture of HDPE were downloaded from the NREL's U.S. LCI database.

6. Conclusions and recommendations

6.1. Conclusions

The use of ACQ-treated lumber for decking offers lower fossil fuel use and environmental impacts than WPC. Compared to an ACQ-treated lumber deck of the same size, and using the assumptions of this LCA, with the understanding that assumptions can vary, use of WPC results in approximately 14 times more fossil fuel use and results in emissions with potential to cause approximately three times more GHG, almost three time more water use, four times more acid rain, over two times more smog, approximately two times more ecological toxicity, and equal the eutrophication potential.

If a family of three adds or replaces a 320 square feet ACQ-treated lumber deck at their home, the impact "footprint" of this action for GHG, fossil fuel, acidification, potential smog forming releases, ecotoxicity, and potential eutrophication releases each is less than one-tenth of a percent of the family's annual total "footprint". If the same deck was constructed of WPC, the impact "footprint" for energy, GHG, fossil fuel use, and smog also would be low for each, but greater than ACQ-treated lumber. The fossil fuel footprint for a 320 square feet deck constructed with ACQ-treated lumber decking equates to driving a car getting 20 miles per gallon (mpg or 8.5 km per liter (km/l)) approximately 38 miles (61 km) per year. For a WPC deck, the fossil fuel footprint equates to driving the same car approximately 540 miles (869) per year.

The total energy use value (including fossil fuel use, biogenic, and renewable resources) of WPC is approximately 8.5 times more than for an ACQ-treated lumber deck surface. The U.S. average family total energy use "footprint" for the surface of a 320 square feet deck is approximately 0.040% of the family total annual energy footprint for the ACQ deck surface and 0.34% for the WPC deck surface. Of the total energy, approximately 50% is from biomass sources and 50% is from fossil fuel sources for ACQ-treated lumber, while nearly all energy for WPC is from fossil fuel.

6.2. Recommendations

Production facilities should continue to strive to reduce energy inputs through conservation and innovation, including sourcing materials from locations close to point of use. Also, the use of biomass as an alternate energy source can reduce some impact category values compared to the use of fossil fuel energy or electricity off the grid.

Use of demolished decking material as fuel has distinct advantages over landfill disposal including: 1) energy produced from the biomass offsets energy production using fossil fuels and their associated impacts; 2) wood mass is not disposed in a landfill resulting in less landfill construction and closure-related impacts; and 3) methane generation from anaerobic decay in a landfill would not occur. Some emissions from the energy production equipment would occur; however, the emissions from such equipment are typically well controlled.

This study includes the comparison of ACQ-treated lumber and WPC used for decking. The results conform with the ISO 14040 and ISO 14044 standards and are suitable for public disclosure. The peer-review Procedures and Findings Report can be requested by contacting the Treated Wood Council at www.treated-wood.org/contactus.html.

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