Journal of Cleaner Production 99 (2015) 217–229

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Cradle-to-gate life cycle impacts of redwood forest resource harvesting in northern California

Han-Sup Han [a,*], Elaine Oneil [b,1], Richard D. Bergman [c,2], Ivan L. Eastin [b,3], Leonard R. Johnson [d,4]

[a] Humboldt State University, Arcata, CA 95515, USA
[b] University of Washington, Seattle, WA 98195, USA
[c] USDA Forest Service Forest Products Laboratory, Madison, WI 53726, USA
[d] University of Idaho, Moscow, ID 83843, USA

A R T I C L E I N F O

Article history:
Received 5 August 2014
Received in revised form
19 February 2015
Accepted 28 February 2015
Available online 13 March 2015

Keywords:
Redwood lumber
Life cycle analysis
Environmental impacts
Fuel consumption in timber harvesting
Air quality impacts

A B S T R A C T

The first life cycle impact assessment for redwood (*Sequoia sempervirens*) forest management activities (i.e. a cradle-to-sawmill gate input) including the growing, harvesting, and hauling of redwood sawlogs to a sawmill was completed. In the stump-to-truck timber harvesting analysis, primary transport activities such as skidding and yarding consumed the largest amount of fuel and consequently generated the greatest environmental impacts (50% of the total) compared with the other harvesting stages (felling, processing, and loading). Hauling sawlogs to the sawmill was also a major contributor to total greenhouse gas emissions, representing 20% of total emissions. The most efficient harvest method in terms of fuel consumption per m^3 of wood harvested was the manual ground-based system used in even-aged silvicultural operations, followed by the skyline harvesting methods. Relative to even-aged silvicultural systems, uneven-aged systems, often prescribed to meet environmental goals such as maintaining biodiversity and protecting wildlife habitats, used 20% more fuel per m^3 of redwood sawlogs harvested. This was because uneven-aged systems required an increased number of entries to harvest the same amount of wood as even-aged systems. The cradle-to-gate GHG emissions from redwood forest management activities including growing, harvesting and hauling the logs represent only 14% (17.13 kg CO_2e/m^3) of the total GHG emissions (i.e. cradle-to-grave) associated with redwood decking lumber. The study results showed substantial differences in environmental impacts for the various harvesting operations and silvicultural systems for redwood forest management and operations. Therefore, the life cycle impact assessment results for the various redwood harvesting and silvicultural systems should be carefully considered when evaluating environmental performance of forest management activities along with other objectives.

1. Introduction

Redwood (*Sequoia sempervirens*) is a unique species that has a limited natural range along the coastal zone of northern California (Berrill et al., 2012). Redwood is commonly used to manufacture outdoor decking because of its natural beauty and superior resistance to decay (Wilcox and Piirto, 1976; Clark and Scheffer, 1983). Consumers choose to use redwood decking or comparable products based on a broad range of product attributes including price, quality, durability and intended service application (Ganguly and Eastin, 2009). In recent decades, the burdens that a particular product may impose on human health and the physical environment are receiving increased consideration. In particular there is increased public interest, and an ongoing debate, regarding the environmental impacts associated with the manufacture, consumption, disposal, and re-use of products that originate from the forest (Bowyer et al., 2014).

* Corresponding author. Tel.: +1 707 497 8497.
E-mail addresses: hh30@humboldt.edu (H.-S. Han), eoneil@uw.edu (E. Oneil), rbergman@fs.fed.us (R.D. Bergman), eastin@uw.edu (I.L. Eastin), lrkmjohnson@frontier.com (L.R. Johnson).
[1] Tel.: +1 206 543 6859.
[2] Tel.: +1 608 231 9477.
[3] Tel.: +1 206 543 1918.
[4] Tel.: +1 208 882 0484.

http://dx.doi.org/10.1016/j.jclepro.2015.02.088
0959-6526/

To make informed product choices consumers need transparent, scientifically verified, objective information. Life cycle inventory (LCI) and life cycle assessment (LCA) are analytical techniques commonly used to quantify the emission profiles and environmental impacts of a wide range of products, respectively. The LCA process is well defined by international standards (ISO, 2006a; 2006b), and has been used extensively over the past decade to quantify the environmental footprint of wood products (Puettmann and Wilson, 2005), link forest management choices to environmental performance indices in the forest (Lippke et al., 2005; Oneil and Lippke, 2010), and track the carbon consequences of wood product manufacturing and use (Lippke et al., 2010). The Consortium for Research on Renewable Industrial Materials (CORRIM) has documented the LCIs of the major wood products manufactured in the US, but no work has been completed for redwood decking products. Existing wood product data are publicly available from the US LCI Database (2012).

This study reports on the environmental impacts of forest resource management activities including the growing, harvesting, and hauling of redwood sawlogs to the sawmill, referred to as a forest resource cradle-to-gate LCA. The forest resource cradle-to-gate LCA we report on here was part of a larger study (i.e. cradle-to-grave) that included the redwood decking product manufacturing processes, transportation to market, product use, maintenance, and final disposal (Bergman et al., 2013). To assess the comprehensive environmental footprint of redwood decking lumber, the framework for data collection used in prior CORRIM studies was adapted to gather the specific information needed to produce the forest resources LCI for redwood decking.

The LCI and LCA methods measure the inputs and outputs per unit of product manufactured so that it is easy to calculate the embodied energy (the amount of energy required to manufacture a product), emissions to land, air and water, and quantify the impacts those emissions may have on the environment and human health (ISO, 2006a; 2006b).

Forest management activities, including timber harvesting and log hauling in California's forests, are required by law to follow the California Forest Practices Rules which are some of the most stringent regulations found in the United States today (Dicus and Delfino, 2003). In addition, all firms surveyed for this project manage their forests consistent with either Forest Stewardship Council (FSC) or the Sustainable Forestry Initiative (SFI) certification standards which have additional requirements beyond those specified in the California regulations. Given the stringent regulations and certification standards under which redwood forests are managed, there is a high likelihood that the forests harvested to produce redwood decking are sustainably harvested and will be for the foreseeable future. For that reason we did not track carbon increases and decreases in the forest as they are anticipated to be negligible under the sustainable management regimes being practiced in California today. Under these assumptions of sustainable forest management following ASTM International standard D7612-10 (2010) and guide D7480-08 (2014), data were gathered that reflect the current state of production and are reported consistent with the protocols identified in the North American Wood Product Category Rule (PCR; FPInnovations, 2013).

Environmental impacts associated with forest management activities are documented for a wide variety of places and tree species (González-García et al., 2014; Dias and Arroja, 2012; Cambria and Pierangeli, 2012) using life cycle inventory and assessment methodologies. Results, some measured and others simulated, show high variability among regions, species, and management system. For example Dias and Arroja (2012) found a global warming potential (GWP) for growth and harvest of pine and eucalyptus in Portugal from 4.8 to 18.5 kg CO_2e/m^3. Cambria and Pierangeli (2012) report a GWP of 120 kg/m^3 for walnut in Italy and Gonzalez-Garcia et al. (2013) report a GWP of 2.3 kg/m^3 including bark for Douglas-fir plantations in Germany. Data from Johnson et al. (2005) and Oneil et al. (2010) were used to calculate GWP for forest management operations in four US regions (Puettmann et al., 2013a,b,c; Puettmann and Oneil, 2013) and found values ranging from 9.41 to 14.52 kg CO_2e/m^3 of logs (without bark). Differences in methodology, boundary condition such as including the fencing (Cambria and Pierangeli, 2012), or excluding hauling (Johnson et al., 2005; Oneil et al., 2010) and functional unit definition (i.e. with and without bark) contribute to this variability. Even with uniform boundary conditions, methodology, and functional unit there can still be substantial differences in environmental performance, largely as a result of yield per hectare, management intensity, and harvest system (Johnson et al., 2005; Oneil et al., 2010; Diaz and Arroja, 2012).

No life cycle analysis has been conducted to quantify the environmental footprint of redwood forest management activities in northern California. Redwood growth, management, and harvesting systems have some unique attributes that have not been quantified elsewhere. For example, in certain visually and environmentally sensitive areas, helicopters are used to remove logs from the forest. The life cycle impact of this harvest system had not been quantified before. Unlike other conifer species in North America redwood sprouts from harvested roots therefore the effort and time to regenerate redwood forests is greatly reduced. With these differences in mind, the goal of this study was to estimate the environmental impacts of redwood forest management activities associated with the growing, harvesting, and hauling of redwood sawlogs that are manufactured into redwood decking lumber. Boundary conditions and functional unit used for this study were the same as those used for Johnson et al. (2005) and Oneil et al. (2010), but primary data which was collected on forest operations on a specific species and region was expected to generate more precise results.

2. Methods

The scope of this cradle-to-gate study was part of a larger cradle-to-grave LCA analysis of redwood decking lumber that focused on the life cycle of redwood forest resources (i.e. sawlog production; Fig. 1). This study conforms to internationally-accepted standards (ISO, 2006a, 2006b), used primary data collected from redwood forest landowners, as well as secondary data from the US LCI Database (2012) which was used to model the LCI of redwood forest resources using the SimaPro program. It includes an evaluation of the following components:

- nursery operations to grow redwood tree seedlings
- fill planting of redwood seedlings
- pre-commercial thinning of redwood forests
- commercial thinning of redwood forests
- commercial harvest of redwood sawlogs
- transportation of redwood sawlogs to sawmills

Some forest residues (i.e. logging slash) generated from timber harvest activities were collected, ground up, and transported to local energy plants when the biomass operations were economically feasible. Since the electricity produced from burning redwood forest residues forms part of the regional power grid that supplies electricity to redwood sawmills, the downstream contribution of the logging slash was accounted for in a separate redwood decking LCA analysis. While the redwood forest residues are an important co-product of the cradle-to-grave redwood decking process, they were not modeled as part of the present redwood harvesting life

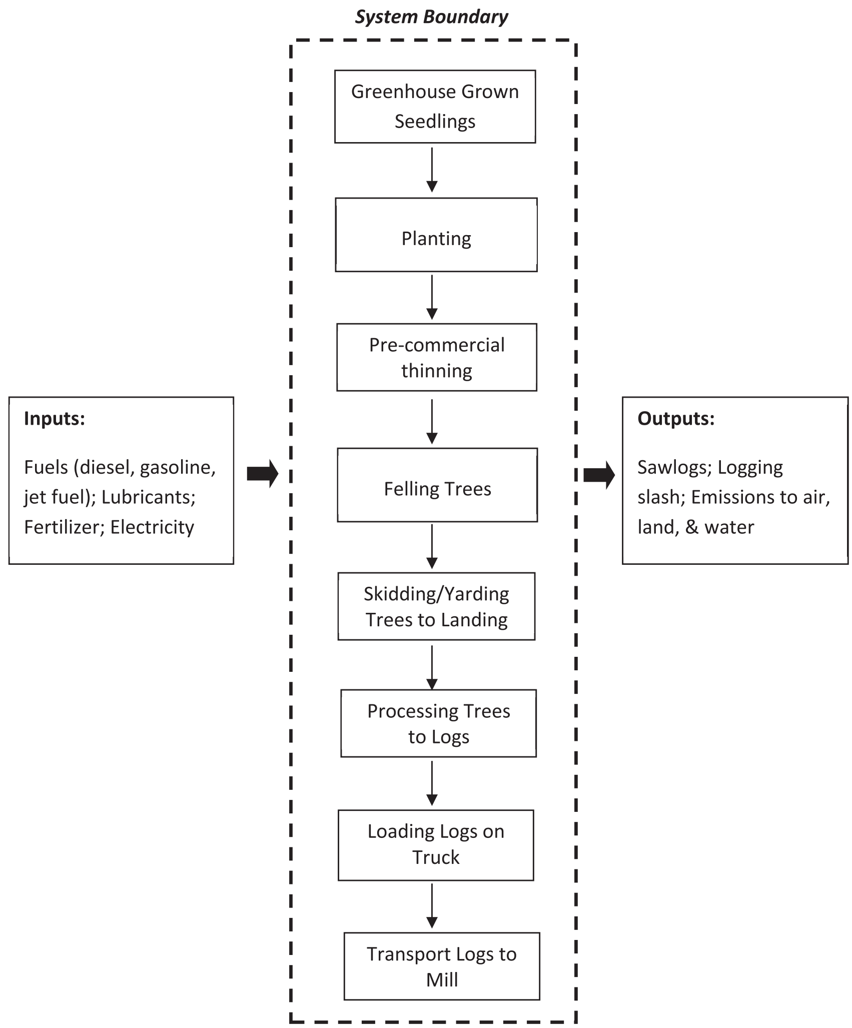

Fig. 1. System boundaries and process flow diagrams. This figure shows the system boundaries and process flow diagrams for forest stand establishment and harvesting of California redwood forests.

cycle impact assessment (LCIA) to prevent double counting of these benefits.

2.1. Life cycle inventory data collection and analysis

LCI data are developed using a variety of techniques. In this study, we collected primary data on forest management and harvesting operations using landowner surveys on four redwood forest products companies in northern California that collectively represent 90% of redwood decking production. Our survey was to develop representative timber harvest and raw material collection data including measures of all material inputs such as labor use, and fuel and lubrication per unit of collection activity. From these survey data we developed scenarios, identified representative equipment profiles, and established average yield values. Yield was used to calculate standing and harvested volume and biomass along with many other stand characteristics at selected points in time throughout the rotation age of the forest stand. Secondary data were synthesized from existing data, including literature reviews, published data sources, government and industry reports, and synthesis of economic data.

The survey questionnaire covered elements of forest resource management including stand establishment, intermediate forest treatment, harvesting system profiles, transportation, and forest residue recovery operations. Questions related to log harvest volumes through the rotation age of the forest stand were also included in the survey. The survey collected data for the year 2010. The primary source of air emissions was from the combustion of diesel fuel, gasoline, and jet fuel that was used to operate the harvest equipment, log trucks and helicopters. Lubricants were consumed through replacement at the end of its life and assumed to be recycled. Emissions related to the fertilizers used to grow the seedlings in the nursery were also estimated.

2.1.1. Stand establishment and forest inventory

Information collected in this section of the survey included nursery operations, seedling planting activities, intermediate treatment activities (fertilization and pre-commercial thinning), types of silvicultural systems used (i.e. even-aged or uneven-aged), rotation ages, and volume removals at each entry.

2.1.2. Harvesting systems and productivity

Landowners were asked to describe typical harvesting systems and the type of equipment used to harvest timber from stump to truck, including felling, primary transport (stump-to-landing), processing, and loading. Three major types of harvesting systems were surveyed: ground-based, skyline, and helicopter. These three harvesting systems were further subdivided based on the equipment type used and the harvest methods (i.e. uneven-aged, even-aged) applied. Questions asked in this section were related to harvesting productivity (i.e. thousand board feet (MBF)/h), cost ($/MBF), and fuel/oil consumption rates for each piece of harvesting equipment used. Machine utilization rates were also surveyed and used to adjust hourly productivity and fuel and lubrication consumption rates.

2.1.3. Log hauling

Log hauling starts with loaded logs at the landing and ends with unloading logs at the sawmill, a process referred to as secondary transport. Survey questions included truck types, horse power, load volume per trip, and average speed of travel on five different road categories (spur, dirt, gravel, 2-lane highway, and interstate highway). Data included machine costs and fuel consumption rates.

2.1.4. Slash treatments and biomass recovery for energy

This section of the survey was used to gather information on activities associated with managing the slash resulting from timber harvest, including percent utilization of trees cut, type of collection equipment used, use of prescribed burning, and biomass recovery operations for energy production. Productivity (ton/h), cost ($/ton), and fuel consumption rates were obtained for biomass recovery equipment and systems that are commonly used to recover forest residues left from redwood sawlog harvesting. The data were used to estimate the annual recovery volume (%) under current market conditions for redwood sawlogs and biomass. Biomass hauling information was gathered using the same questions that were used for log transportation.

The survey information was aggregated and summarized to calculate weighted average values which represent the mean value for each category of interest. Each category of the survey information was weighted based on each company's annual harvest volume, silvicultural methods (uneven-aged or even-aged), and the type of harvest system used (Fig. 2). The survey data summary and initial calculation values were entered into the Harvest Factors spreadsheet detailing the input parameters needed for a complete forest resource LCI (Johnson, 2008). The spreadsheet framework was developed for previous CORRIM reports that summarize the LCI for wood products in the US (Johnson et al., 2005; Oneil and Lippke, 2010).

2.2. Life cycle impact assessment

Data from the Harvest Factors spreadsheets were entered into LCA modeling software package SimaPro 7.3 (PRé Consultants, 2013) which was used to estimate the environmental impacts to the air and water from the redwood forest management activities. Primary data summarized in the Harvest Factors spreadsheet were entered into the SimaPro program using a functional unit of m^3 for sawlogs. Key input values included fuel and lubrication consumption rates and volume of logs removed/hectare that varied based on harvesting systems and silvicultural methods used. Each harvesting system consisted of a set of machines which are commonly used to harvest redwood sawlogs in northern California, with each machine consuming different amounts of fuel and lubricant.

The LCIA was summarized using the TRACI 2 v3.0 (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) impact estimator which was developed by the US Environmental Protection Agency (Bare, 2011). The impacts were grouped into indicators including: global warming potential (GWP), ozone depletion, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, ecotoxicity and respiratory effects. Each environmental impact category was measured relative to a common reference unit: GWP (carbon dioxide equivalents, CO_2e); ozone depletion (chlorofluorocarbon equivalents, CFC); smog (ozone, O_3); acidification (mole of hydrogen ions, H+); carcinogenics (benzene equivalents); non-carcinogenics (toluene equivalents); and ecotoxicity (2.4-D equivalents). Respiratory effects were quantified relative to the emissions of particulate matter that was greater than or equal to 2.5 microns in size (PM 2.5). Eutrophication, the only impact category reported that was specific to emissions to water, measures the impact of nitrogen emissions on water quality and is reported in nitrogen equivalents (N-eq). The TRACI method does not account for carbon dioxide emissions from burning biomass consistent with existing EPA regulations. However, it does track other emissions associated with burning biomass, such as those from methane.

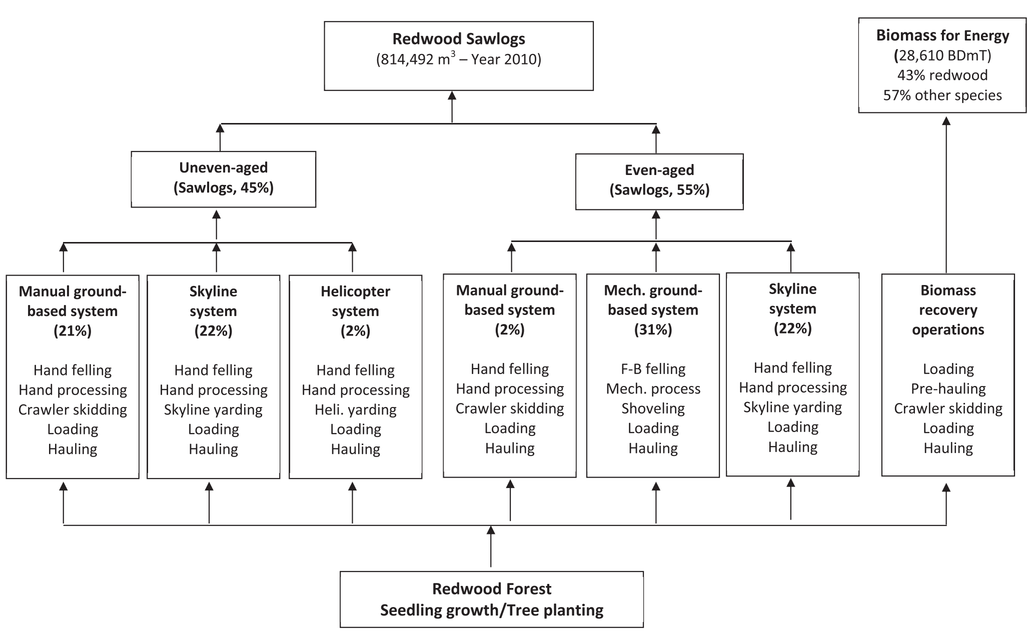

Fig. 2. Redwood forest operations. This figure shows the redwood forest operations producing sawlogs and biomass using different silvicultural methods and harvesting systems.

2.3. Carbon accounting

Biomass in general and forests in particular have a large capacity to remove CO_2 from the atmosphere and store it in wood as a stable form of carbon while releasing oxygen back into the atmosphere. This process is referred to as carbon sequestration and because of the perceived benefit of forests as carbon sinks, great interest has been shown regarding the forest carbon uptake and CO_2 releases related to various forest management and harvest practices. Carbon uptake can be derived from the mass balance of wood and its constituent components and is based on a simple formula that includes specific gravity, the carbon content of wood, and the ratio of carbon in a CO_2 molecule. The carbon uptake factor calculated as part of this study was derived from the following equation:

$$\text{Carbon uptake factor for round wood } (\text{kg } CO_2e) = \text{vol}\cdot\text{sg}\cdot 1000\cdot CO_2\cdot C$$

Where,

- vol = volume of wood harvested (m^3)
- sg = specific gravity of wood = 0.36 for green redwood logs when harvested
- 1000 = converting from specific gravity to a unit of kg/m^3 CO_2 = 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)
- C = carbon content of wood = 0.53 as the mass of C per oven dry unit of redwood (Jones and O'Hara, 2012)

The carbon uptake factor reflects how much carbon dioxide equivalent (CO_2e) is stored in the final wood product which can then be compared to the amount of CO_2e emitted during the production process. The amount of carbon uptake stored in the growing trees was not included in calculating GWP in the present (cradle-to-gate) study. Using the carbon uptake equation, the CO_2 sequestered in the log plus bark was calculated for each silvicultural system and a weighted average was generated for all logs delivered to the sawmill. Bergman et al. (2013) estimated bark at 9.9% of the wood volume with about 40% of the bark lost during log handling. This lost bark was included in the carbon uptake calculation. For one m^3 of harvested redwood logs delivered to the mill gate, the amount of carbon stored (including the bark) was equivalent to 1400 kg CO_2 (Bergman et al., 2013).

2.4. Limitations of study

Since today's redwood harvest takes place predominantly in second growth forests, we assumed that forest roads were already in place. Forest roads also serve as infrastructure to support various forest management activities that produce an array of wood products. For these reasons the environmental effects of building and maintaining forest roads were not included in the analysis. Manufacturing and installing capital equipment and buildings have generally a minor effect on the environment relative to the throughput of products over the useful lives of the machines and buildings (Mahalle and O'Connor, 2009), and therefore were also excluded from the life-cycle analysis.

3. Results

Survey data were used to calculate weighted average values for the forest management scenarios outlined in Tables 1–3. Information collected included data on nursery operations (Table 1), seedling planting activities (Table 2), and intermediate treatment activities (fertilization and pre-commercial thinning), silvicultural systems used, rotation ages, and volume removed at each entry (Table 3). These data were collected on a per seedling and per ha basis and then allocated to a per m^3 functional unit basis based on the amount of log volume recovered for each silvicultural and harvesting system reported in the survey.

Table 1
Fertilization rates to grow coast redwood 2-year old seedlings in a tree nursery. The values of grams/ha are based on the planting rate of 339 seedlings per ha of even-aged forestland.

	Nitrogen (N)	Phosphate (P)	Potassium (K)
Fertilization (grams/ha)	137.19	124.96	208.50
(grams/seedling)	0.4040	0.3680	1.6140

3.1. Timber harvest and biomass recovery operations

The redwood forest resource LCI provides weighted average values for all inputs and outputs based on the percent allocation between the silvicultural and harvesting systems that were used to harvest redwood logs in northern California. The weighted average values shown in Fig. 2 were determined from the data reported in the 2010 surveys.

Silvicultural systems were classified into two general categories: even-aged and uneven-aged. Within these categories there were several variations that were driven by the inherent characteristics of the trees that were being managed and the environmental conditions that the trees encountered. In northern California, both even-aged and uneven-aged systems were used in redwood forests. The even-aged systems used clear-cutting at the final harvest to remove logs and open the area for regeneration. For even-aged systems, the final harvest generally occurred at age 50 using the clear-cut method. The uneven-aged systems employed various levels of thinning to harvest fewer trees at shorter intervals to promote regeneration under the canopy of the existing forest. For uneven-aged systems, harvesting generally occurred at 20 year intervals for trees that are 60 years old. In 2010, a total of 814,492 m^3 of redwood sawlogs were harvested by survey respondents using both the uneven-aged (45%) and even-aged (55%) silvicultural systems (Fig. 2).

There were four harvesting systems that were commonly used to harvest redwood logs in northern California: manual ground-based, mechanized ground-based (shovel yarding), skyline and helicopter systems. Both manual and mechanical ground-based systems were used to harvest trees on gentle slopes (<40% slope) while steep slopes (>40% slope) usually required the use of a skyline yarding system. Helicopter harvesting was occasionally used for environmentally sensitive areas or for long yarding distances (>1000 m) due to the lack of forest roads. The skyline yarding system was used more often (44% – even and uneven-aged combined) than any other harvest systems in 2010, followed by mechanized ground-based (31%), and manual ground-based (23%). The helicopter system was used to harvest only 2% of the total harvest in 2010.

Based on our survey, a total of 28,610 bone dry metric tons (BDmT) of logging slash was collected and delivered to local energy

Table 2
Fuel and lubricant consumption rate for tree planting and pre-commercial thinning.

	Gasoline (liters/ha-km)	Lubricant (liters/ha-km)
Tree planting[a]	0.05535	0.00100
Pre-commercial thinning	0.09300	0.00167

[a] Based on average distance from a seedling storage place to planting sites.

Table 3
Assumptions and input values used for the environmental impact analysis of redwood forest resources management. Input values were compiled from responses on survey forms.

	Uneven-aged	Even-aged
Age of trees (years)	40–100+	50
Fertilization of trees	None	None
Harvest volume (% total)	47	53
Harvest volume (m^3/ha) per entry	100.13	290.17
Harvest unit size (ha)	14	10
Seedling planting density (trees per ha)	339	
Estimate of bark as percent of solid wood: 9.9% after accounting for handling losses[a]		
Average skidding/yarding distance: 202 m for all harvesting systems used		
One-way sawlog hauling distance: 52 km on average		
Specific gravity (green): 0.36[b]		
Carbon fraction (mass of carbon per unit mass of dry wood): 0.53[c]		

[a] Bergman et al. (2013).
[b] Miles and Smith (2009).
[c] Jones and O'Hara (2012).

plants in 2010. Of that volume, 43% (or 12,302 BDmT) was redwood logging slash (Fig. 2). Relative to even-aged operations, thinning generated less logging slash making it more uneconomical and therefore it was less common for biomass collection to occur in forests that have been thinned. Even for even-aged units which generate a high volume (100–240 ton/ha) of logging slash, the economics of logging slash recovery operations and transportation were not favorable given the current market value of ground slash ($45/BDmT) in the region. Despite the poor economic returns, logging slash recovery was sometimes used as a site preparation technique in place of burning the logging slash on site. Burning biomass from agricultural and forestry sources for electricity represents 1.8% (2008 e-grid data) of the California grid (EPA, 2012) and therefore the gains from using this material for generating electricity are already represented in the e-grid data used in the LCA analysis. For that reason, the electricity produced from burning redwood forest residues was not included in the LCIA.

3.2. Fuel and lubricant consumption during harvesting activities

Surveys indicated that uneven-aged silvicultural systems that rely on thinning used less fuel and lubricant to perform harvest operations than did even-aged systems that rely on clear-cut methods, but hourly harvesting production rates (m^3/h) for thinning operations were lower than for clear-cutting operations. These differences resulted in higher fuel and lubricant consumption per m^3 of redwood sawlogs harvested for uneven-aged harvest systems compared to even-aged silvicultural systems (Table 4). For the skyline method, there was 20.19% more fuel used per m^3 of logs harvested for the uneven-aged system compared to an even-aged system. Skyline harvesting system used the same or similar equipment for both uneven-aged and even-aged systems.

There were also large differences in harvesting productivity and fuel consumption among the logging systems used to harvest redwood timber in northern California. The helicopter system consumed substantially more fuel and lubricant than any other system. Helicopter yarding alone consumed 624.59 L per hour. Helicopter yarding productivity was also the highest of all systems (37.93 m^3/h in uneven-aged system), resulting in 16.46 L of fuel consumption per m^3 of wood harvested, which was approximately six times the weighted average for all other yarding systems. However, the helicopter systems also operated over longer average yarding distances than the ground-based or skyline systems. The most efficient harvest method in terms of fuel consumption/m^3 of wood harvested was the manual ground-based system used in even-aged silvicultural operations, followed by skyline harvesting methods. The mechanized ground-based harvesting system used a high volume of fuel (130.97 L per hour) for stump-to-truck harvesting (second highest after helicopter logging), with a corresponding high production volume. This system was therefore more efficient on a liter/m^3 basis than both the manual ground-based and skyline systems that were used for thinning in uneven-aged silvicultural operations (Table 4).

On a per m^3 basis, the primary transport activities (e.g., skidding and yarding) used the highest amounts (40–93%) of the total fuel consumed for the stump-to-truck harvest, followed by loading, felling and processing. Fuel and lubricant consumption for primary transport activities was highly dependent on the skidding or yarding distance which varied by terrain and therefore by the type of system used. The survey results indicated that the average yarding distances for each harvesting system were: ground-based (100–450 m); skyline (230–450 m); and helicopter (600–1500 m). Using the mid-point of these ranges, fuel consumption rates for primary transport in uneven-aged silvicultural operations were 0.0118, 0.0088, and 0.0157 L/m^3 per m of one way yarding distance for the ground-based, skyline and helicopter systems, respectively. The overall average yarding distance, weighted based on the harvest volume using each harvesting system, was 202 m. Gasoline powered chainsaws were the most common tool for felling and processing redwood logs: 77% of the felling and processing tasks were performed using a chainsaw. Helicopters used jet fuel while all other harvesting equipment and log truck used diesel fuel.

The most common method used for logging slash recovery operations in northern California consisted of a loader placing slash into modified dump trucks that hauled the slash to a centralized grinding location. The slash was then ground using a grinder and loaded onto large vans for transport to an energy plant. The 1050-horse power grinder burned 3.68 L of fuel per 27.21 BDmT of slash processed, which represented 60.8% of the total fuel consumed during the stump-to-truck biomass recovery operation. The average haul distance for the modified dump trucks was 1.28 km with a fuel consumption rate of 0.93 L/BDmT.

3.3. Transportation of sawlogs and biomass

Hauling sawlogs and biomass used different transportation methods. A 475-horse power, stinger-steered logging truck was commonly used to haul sawlogs from the forest landing to the sawmill. A 92-m^3 capacity highway-chip van was used for hauling biomass from a grinding location to an energy plant. Hauling routes were classified into five road categories to account for the variation in average traveling speed by road category. The distance traveled on each road class and average traveling speed was used to calculate a total round trip time which determined the amount of fuel and oil consumed. The five road categories for hauling sawlogs were: spur roads (0.8 km at 17.54 km/h), dirt roads (3.22 km at 20.92 km/h), gravel roads (11.43 km at 32.19 km/h), 2-lane highway (14.65 km at 55.84 km/h), and interstate freeway (22.53 km at 81.27 km/h). Chip vans traveled on only three different road categories: gravel roads (16.09 km at 32.19 km/h), 2-lane highway (3.22 km at 55.84 km/h), and interstate freeway (56.33 km at 81.27 km/h). The fuel and lubricant consumption rates in Table 5 are average values for log transportation including loading and unloading times.

3.4. Carbon uptake

The average volume of material harvested was calculated as part of the evaluation and the volume varied considerably depending on the silvicultural system used. Redwood log yielded averaged

Table 4
Hourly productivity and fuel and lubricant consumption rates for redwood harvesting systems. The values presented in this table were based on each entry into the redwood stand to harvest redwood sawlogs and collect logging slash in 2010.

		Machine type	Production rate	Fuel use[a]		Lubricant use[a]
			(m^3/h)	(Liter/h)	(Liter/m^3)	(Liter/m^3)
Uneven-aged (entering every 20-year)	*Manual ground-based system*					
	Felling	Chainsaw	5.30	1.25	0.2384	0.0043
	Skidding	Tracked crawler	7.14	26.50	3.2537	0.0586
	Processing	Chainsaw	13.60	2.54	0.0482	0.0009
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*51.48*	*4.4673*	*0.0804*
	Skyline system					
	Felling	Chainsaw	5.30	1.25	0.2384	0.0043
	Yarding	Skyline yarder	9.93	23.09	3.0034	0.0541
	Processing	Chainsaw	13.60	2.54	0.0482	0.0009
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*48.07*	*4.2170*	*0.0759*
	Helicopter system					
	Felling	Chainsaw	5.30	1.25	0.2384	0.0043
	Yarding	Helicopter	37.93	624.59	16.4649	0.2964
	Processing	Chainsaw	13.60	2.54	0.0482	0.0009
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*649.57*	*17.6785*	*0.3182*
Even-aged (entering every 50-year)	*Manual ground-based system*					
	Felling	Chainsaw	6.03	1.89	0.3141	0.0057
	Skidding	Tracked crawler	12.11	22.33	2.0824	0.0375
	Processing	Chainsaw	18.93	1.85	0.0364	0.0007
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*47.28*	*3.3598*	*0.0605*
	Mechanized ground-based system					
	Felling	Feller-buncher	38.85	37.85	0.8185	0.0147
	Yarding	Shovel	19.37	37.85	1.6008	0.0288
	Processing	Delimber	38.74	34.07	0.7321	0.0132
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*130.97*	*4.0783*	*0.0734*
	Skyline system					
	Felling	Chainsaw	6.03	1.89	0.3141	0.0057
	Yarding	Skyline yarder	12.80	31.04	2.2311	0.0402
	Processing	Chainsaw	18.93	1.85	0.0364	0.0007
	Loading	Log loader	22.87	21.20	0.9270	0.0167
	System total (stump-to-truck)			*55.99*	*3.5085*	*0.0632*
Biomass recovery operation			(BDmT[b]/h)	(liter/h)	(liter/BDmT[b])	(liter/BDmT[b])
	Landing to intermediate load site					
	Loading:	Loader	30.41	21.84	0.7177	0.0129
	Pre-hauling	Dump truck	13.82	34.83	0.9364	0.0169
	Centralized grinding					
	Feeding:	Loader	30.41	21.84	0.7177	0.0129
	Processing:	Horizontal grinder	27.21	100.28	3.6849	0.0663
	System total (stump-to-truck)			*178.78*	*6.0567*	*0.1090*

[a] Including machine idling time (i.e. scheduled machine hour – SMH).
[b] Bone dry metric ton.

100.13 m^3/ha on a 20-year interval as part of an uneven-aged silvicultural system while even-aged silvicultural systems removed 290.17 m^3/ha of redwood sawlogs at each 50-year interval. In mixed conifer stands, additional volumes of other timber species were removed during harvest, but this timber volume was not included in this analysis which was focused solely on redwood as an input into redwood decking production (Bergman et al., 2014).

The total carbon uptake in the redwood forests that were managed using an uneven-aged silvicultural system was 77,894 kg/ha over 20 years or 3895 kg/ha-yr while it was 225,740 kg/ha over 50 years or 4515 kg/ha-yr in the redwood forests that were managed using an even-aged silvicultural system. The differences in carbon uptake between the two systems reflected the difference in the log volume removed on a per hectare basis since uneven-aged systems removed about one-third of the total standing trees

Table 5
Hourly productivity and fuel and lubricant consumption rates for hauling redwood sawlogs and biomass in 2010.

Product type	Hauling truck and one-way distance		Production rate	Fuel use[a]		Lubricant use[a]
Sawlogs	Landing to sawmills		(m^3/h)	(liter/h)	(liter/m^3)	(liter/m^3)
	Hauling at 52 km	Stinger-steered truck	8.49	20.41	2.4040	0.0433
Biomass	Transportation from central grinding site to energy plant		(BDmT[b]/h)	(liter/h)	(liter/BDmT[b])	(liter/BDmT[b])
	Hauling at 76 km	Chip van – 92 m^3/trip	4.44	33.04	7.4429	0.1340

[a] Including machine idling time (i.e. scheduled machine hour – SMH).
[b] Bone dry metric ton.

at each entry whereas even-aged systems removed all trees in areas designated for harvest during each entry. For even-aged systems, some trees were retained for water quality protection and to provide habitat functionality along designated riparian zones and wildlife areas adjacent to harvest areas.

3.5. Life cycle inventory and life cycle impact assessments from redwood forest management activities

The emissions to air values reported in the LCI for the six different harvesting operations and the log hauling operational stage are summarized in Table 6. The environmental impact results for GWP, acidification, carcinogenics, non-carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity and smog are shown in Table 7, for each silvicultural system, harvesting method, and operations phase with a total weighted average and percent allocation by the sawlog volume harvested in 2010. While there were slight variations in the individual impact indicator rankings between the silvicultural systems, harvest methods, and operations, all followed a pattern similar to that shown for GWP in Fig. 3 and therefore we used GWP as an example to explain the environmental impact differences between harvest systems and methods. Fig. 3 shows that uneven-aged silvicultural systems had slightly higher greenhouse gas emissions (GHGs) measured in kg of CO_2e as compared to the even-aged silvicultural systems. This was most noticeable with the helicopter harvesting operations. The GHG emissions from the other harvesting systems were similar, ranging from 14.21 kg CO_2e (manual ground-based, even-aged) to 17.76 (manual ground-based, uneven-aged) kg CO_2e. These variations were directly correlated to the number of entry for timber harvesting and the amount of fuel and lubricant consumed per m^3 of logs during harvesting operations.

Transporting the log or tree from stump to a landing (i.e. skidding and yarding), referred as to primary in-woods transport, generated the highest level of environmental impacts, almost 50% of the GWP (Fig. 4). The second highest level (about 20%) of emissions was generated from hauling logs from the landing area to the sawmill, based on an average 52-km one way hauling distance. The environmental impacts generated from stand establishment activities were minimal at less than 2% of the total impacts. The weighted average GHG emissions emitted from stand establishment, harvesting, and hauling activities to supply redwood sawlogs to sawmills was 17.13 kg CO_2e/m^3 which is consistent with roundwood supply chain results reported by Handler et al. (2014) and Timmermann and Dibdiakova (2014). Since that same m^3 of redwood logs contains 1400 kg CO_2e, the net balance of the system was a −1382.7 kg CO_2e and the carbon stored in the logs was 81.7 times (=1400/17.13 kg CO_2e/m^3) the GHG released during these operations. In other words, the amount of carbon stored (sequestered) in the final wood product far exceeded the amount of carbon released into the atmosphere during the planting, thinning, harvesting and hauling of the logs to the sawmill.

3.6. Environmental impacts from logging slash recovery and hauling operations

The LCI calculated emissions to air, water or land from logging slash recovery and hauling operations (Table 8). The LCIA results for the same operations are given in Table 9. Hauling biomass to an energy plant over a 76 km one-way hauling distance resulted in higher impacts for all nine impact categories (55.1% of the total) on the environment than did all the other logging slash recovery operation activities combined. These results were largely due to the amount of fuel consumed during the transport phases associated with the slash recovery operation (0.109 L/BDmT) in the forest and transporting the ground biomass to the power generation facility (0.134 L/BDmT). In addition, the grinding process represented the second largest contribution to the impact categories, accounting for 27.3% of the total environmental impact.

4. Discussion

On a per m^3 basis, primary in-woods transport activities such as skidding and yarding represented the largest fuel consuming activities in stump-to-truck timber harvesting operations, ranging from 39% (mechanized ground-based system for even-aged) to 93% (helicopter system for uneven-aged) of the total fuel consumption (Table 4). Skyline yarding activities for even-aged and uneven-aged used approximately 64% and 71%, respectively, of the total fuel consumption for each m^3 of redwood sawlogs harvested. It should be noted that the helicopter yarding distances (600–1500 m) were much longer than the distance used for the ground-based (100–450 m) and skyline systems (230–450 m), which explains in part the increase in fuel consumption for helicopter yarding relative to ground-based and skyline harvesting systems. Helicopter harvesting is often used in environmentally sensitive areas such as riparian zones and roadless areas because it causes little soil disturbance as the logs are lifted into the air and there is no log

Table 6
Emissions (kg) to air per m^3 of redwood logs from six different harvesting systems used in uneven-aged and even-aged silvicultural systems and hauled 52 km to a sawmill.

Emissions to air	Uneven-aged			Even-aged			Log hauling
	Manual ground-based	Skyline	Helicopter	Manual ground-based	Mechanical ground-based	Skyline	
Aldehydes, unspecified	1.73E-04	1.63E-04	5.63E-04	1.30E-04	1.59E-04	1.36E-04	4.09E-05
Ammonia	8.71E-05	8.22E-05	2.83E-04	6.57E-05	8.02E-05	6.85E-05	2.06E-05
Carbon dioxide, biogenic	1.01E-02	9.51E-03	3.28E-02	7.59E-03	9.27E-03	7.92E-03	2.38E-03
Carbon dioxide, fossil	1.36E+01	1.29E+01	4.45E+01	1.02E+01	1.26E+01	1.07E+01	3.26E+00
Carbon monoxide, fossil	1.65E-01	1.59E-01	3.98E-01	1.44E-01	1.21E-01	1.48E-01	2.83E-02
Formaldehyde	8.93E-05	8.44E-05	2.72E-05	6.74E-05	8.23E-05	7.03E-05	2.11E-05
Hydrogen chloride	1.28E-04	1.21E-04	4.18E-04	9.68E-05	1.18E-04	1.01E-04	3.04E-05
Isoprene	2.53E-04	2.39E-04	8.23E-04	1.91E-04	2.33E-04	1.99E-04	5.98E-05
Methane, fossil	1.57E-03	1.50E-03	2.65E-03	1.31E-03	1.25E-03	1.35E-03	3.01E-04
Nitrogen oxides	2.46E-01	2.32E-01	2.86E-01	1.83E-01	2.30E-01	1.91E-01	5.94E-02
Particulates, >2.5 um, and <10um	7.28E-03	6.85E-03	2.55E-03	5.30E-03	7.02E-03	5.55E-03	1.83E-03
Particulates, unspecified	1.32E-03	1.24E-03	4.29E-03	9.93E-04	1.21E-03	1.04E-03	3.12E-04
Propene	1.94E-04	1.83E-04	5.45E-05	1.46E-04	1.78E-04	1.52E-04	4.58E-05
Sulfur dioxide	7.03E-03	6.64E-03	2.28E-02	5.31E-03	6.48E-03	5.54E-03	1.66E-03
Sulfur oxides	1.39E-02	1.31E-02	3.72E-02	1.05E-02	1.28E-02	1.09E-02	3.29E-03
VOC, volatile organic compounds	7.19E-03	6.83E-03	3.88E-03	5.68E-03	6.21E-03	5.89E-03	1.56E-03
Total	14.10	13.31	45.29	10.59	13.04	11.06	3.35

Table 7
Impact assessment associated with stand establishment, harvesting, and transportation to supply 1-m^3 of redwood sawlogs to sawmills.

Operations phase	Impact category[a]	Uneven-aged			Even-aged			Total	
		Manual ground-based system	Skyline system	Helicopter system	Manual ground-based system	Mechanical ground-based system	Skyline system	Weighted[b]	(%)[c]
Stand	Global warming	0.2391	0.2391	0.2391	0.2475	0.2475	0.2475	0.2437	1.42
	Acidification	0.1429	0.1429	0.1429	0.1479	0.1479	0.1479	0.1457	1.15
	Carcinogenics	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	1.47
	Non carcinogenics	1.8255	1.8255	1.8255	1.8898	1.8898	1.8898	1.8609	1.47
	Respiratory effects	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	1.20
	Eutrophication	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	1.62
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.45
	Ecotoxicity	0.0504	0.0504	0.0504	0.0522	0.0522	0.0522	0.0514	1.46
	Smog	0.0035	0.0035	0.0035	0.0036	0.0036	0.0036	0.0035	1.20
Felling	Global warming	0.6555	0.6555	0.6555	0.8637	2.6092	0.8637	1.3111	7.65
	Acidification	0.3933	0.3933	0.3933	0.5182	2.0182	0.5182	0.9270	7.31
	Carcinogenics	0.0002	0.0002	0.0002	0.0003	0.0009	0.0003	0.0005	7.75
	Non carcinogenics	5.0145	5.0145	5.0145	6.6068	19.2641	6.6068	9.8140	7.74
	Respiratory effects	0.0004	0.0004	0.0004	0.0006	0.0022	0.0006	0.0010	7.32
	Eutrophication	0.0004	0.0004	0.0004	0.0005	0.0021	0.0005	0.0010	7.24
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	7.74
	Ecotoxicity	0.1392	0.1392	0.1392	0.1834	0.5349	0.1834	0.2725	7.74
	Smog	0.0096	0.0096	0.0096	0.0127	0.0470	0.0127	0.0220	7.44
Primary	Global warming	10.3723	9.5743	42.5113	6.6383	5.1031	7.1124	8.4142	49.10
	Acidification	8.0228	7.4056	11.6267	5.1347	3.9472	5.5013	6.0832	47.96
	Carcinogenics	0.0037	0.0034	0.0150	0.0024	0.0018	0.0025	0.0030	49.00
	Non carcinogenics	76.5786	70.6876	315.9924	49.0111	37.6762	52.5109	62.1649	49.04
	Respiratory effects	0.0087	0.0081	0.0142	0.0056	0.0043	0.0060	0.0066	48.02
	Eutrophication	0.0083	0.0077	0.0111	0.0053	0.0041	0.0057	0.0063	47.67
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	49.04
	Ecotoxicity	2.1263	1.9627	8.7752	1.3608	1.0461	1.4580	1.7261	49.04
	Smog	0.1869	0.1725	0.2279	0.1196	0.0919	0.1281	0.1408	47.71
Processing	Global warming	0.1325	0.1325	0.1325	0.1001	2.3338	0.1001	0.8071	4.71
	Acidification	0.0795	0.0795	0.0795	0.0601	1.8052	0.0601	0.6098	4.81
	Carcinogenics	0.0000	0.0000	0.0000	0.0000	0.0008	0.0000	0.0003	4.72
	Non carcinogenics	1.0138	1.0138	1.0138	0.7656	17.2306	0.7656	5.9815	4.72
	Respiratory effects	0.0001	0.0001	0.0001	0.0001	0.0020	0.0001	0.0007	4.80
	Eutrophication	0.0001	0.0001	0.0001	0.0001	0.0019	0.0001	0.0006	4.79
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	4.72
	Ecotoxicity	0.0282	0.0282	0.0282	0.0213	0.4784	0.0213	0.1661	4.72
	Smog	0.0020	0.0020	0.0020	0.0015	0.0420	0.0015	0.0143	4.83
Loading	Global warming	2.9551	2.9551	2.9551	2.9551	2.9551	2.9551	2.9551	17.25
	Acidification	2.2858	2.2858	2.2858	2.2858	2.2858	2.2858	2.2858	18.02
	Carcinogenics	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	17.22
	Non carcinogenics	21.8177	21.8177	21.8177	21.8177	21.8177	21.8177	21.8177	17.21
	Respiratory effects	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	17.96
	Eutrophication	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	17.97
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	17.21
	Ecotoxicity	0.6058	0.6058	0.6058	0.6058	0.6058	0.6058	0.6058	17.21
	Smog	0.0532	0.0532	0.0532	0.0532	0.0532	0.0532	0.0532	18.04
Hauling	Global warming	3.4046	3.4046	3.4046	3.4046	3.4046	3.4046	3.4046	19.87
	Acidification	2.6334	2.6334	2.6334	2.6334	2.6334	2.6334	2.6334	20.76
	Carcinogenics	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	19.84
	Non carcinogenics	25.1363	25.1363	25.1363	25.1363	25.1363	25.1363	25.1363	19.83
	Respiratory effects	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	0.0029	20.69
	Eutrophication	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	20.70
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	19.83
	Ecotoxicity	0.6979	0.6979	0.6979	0.6979	0.6979	0.6979	0.6979	19.83
	Smog	0.0613	0.0613	0.0613	0.0613	0.0613	0.0613	0.0613	20.78
Total	Global warming	17.7592	16.9613	49.8982	14.2094	16.6534	14.6834	17.1360	100.00
	Acidification	13.5578	12.9406	17.1617	10.7801	12.8377	11.1467	12.6849	
	Carcinogenics	0.0063	0.0060	0.0176	0.0051	0.0059	0.0052	0.0061	
	Non carcinogenics	131.3866	125.4955	370.8003	105.2273	123.0147	108.7271	126.7753	
	Respiratory effects	0.0148	0.0141	0.0202	0.0117	0.0140	0.0121	0.0138	
	Eutrophication	0.0141	0.0135	0.0168	0.0112	0.0134	0.0116	0.0132	
	Ozone depletion	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Ecotoxicity	3.6478	3.4842	10.2967	2.9214	3.4153	3.0186	3.5198	
	Smog	0.3165	0.3021	0.3575	0.2519	0.2992	0.2605	0.2952	

[a] Units for impact categories are as follows: Global warming, kg CO_2; Acidification, H+ moles; Carcinogenics, kg benzene; Non-carcinogenics, kg toluene; Respiratory effects, kg PM2.5; Eutrophication, kg N; Ozone depletion, kg CFC-11; Ecotoxicity, kg 2.4-D; Smog, g NOx. All units are equivalent to the unit that is stated for each category.
[b] The weighted total was calculated based on % volume harvested using each harvesting system.
[c] Percentages were calculated for each impact category.

dragging or machine travel in the woods. The trade-off in using this kind of harvest system to reduce soil disturbance and maintain visual aesthetics is that it generates LCI impacts that are much higher than any other harvesting system per m^3 of wood harvested. The impact from helicopter yarding was higher than other primary transport systems evaluated across all the LCI categories we evaluated (Table 7).

It was expected that primary transport activity would use the most fuel of all timber harvesting activities because of the heavy-duty machines utilized in these operations and because this activity was the most time-consuming of all of the timber harvesting activities. However, the percentage was highly variable, reflecting differences in machine types and silvicultural methods used as well as skidding or yarding distances. Johnson et al. (2005) presented similar outcomes to these findings, but the percentages for those were not reported.

Silvicultural systems used also directly affected fuel consumption during timber harvesting activities. Uneven-aged systems required more frequent entries to the forest stand over the life of the stand while harvesting less volume per entry, as compared to even-aged. Uneven-aged system using skyline thinning operations removed less volume and used about the same amount of fuel per hour, which resulted in 4.2 L/m^3 of fuel being consumed whereas the same method used during the final harvest in an even-aged system used 3.5 L of fuel per m^3 of logs harvested. This represented a 20% increase in fuel consumption for sawlog harvesting in uneven-aged over even-aged systems. Although an uneven-aged system is often prescribed to meet environmental goals such as maintaining biodiversity and protecting wildlife habits, it resulted in higher air quality impacts compared to even-aged silvicultural systems (Table 7 and Fig. 3). This increase was largely driven by increased fuel usage due to the increased number of entries into the stand, efficiency losses caused by having to work around residual trees, and removal of less volume per unit area compared to an uneven-aged system.

Excluding hauling, the weighted average GWP for redwood harvesting (13.73 kg CO_2e) (Table 7) was higher than the comparable values for the Pacific Northwest (9.41), Southeast (11.32), and Inland Northwest (10.14) regions, but lower than the Northeast (14.52) region of the US (Puettmann et al., 2013a,b,c; Puettmann and Oneil, 2013) when taking into account the same boundary condition (i.e. excluding hauling logs to the sawmill as was done in the other US regions.)

Hauling sawlogs and biomass to a market was a major contributor to the emission impacts associated with forest management activities. Of the total environmental impacts associated with harvesting and transportation activities, sawlog transportation to the sawmill and biomass transportation to the power generation facility represented 20% and 55% of the total, respectively (Tables 7 and 9). Biomass transportation showed a higher percentage than sawlog transportation because the hauling distance for biomass was longer (76 km vs. 52 km) and the hourly fuel consumption for a truck with chip van was higher (33.04 L vs. 20.41 L) than for a log truck. The one-way forest road distances for hauling sawlogs and biomass reported for this study were 15.4 and 19.2 km, respectively. This distinction was important because hauling speeds were slow (16–40 km/h) on forest roads. These included spur, single-lane and double-lane dirt and gravel roads and the resulting fuel consumption per hour was higher than for paved highway roads. Fuel consumption for hauling sawlog and biomass increases with hauling distance, but the relationship was generally non-linear because consumption was determined not only by hauling distance but also by road conditions and road type (e.g., dirt forest road vs. paved highway). For example, Johnson et al. (2012) noted that the overall whole tree chipping fuel consumption increased to 16.23 L/BDmT over a distance of 145 km compared to 8.52 L/BDmT for a distance of 48 km. For this reason an analysis based on time traveled on each road type combined with total distance was used to accurately assess the relative impacts associated with transportation.

Biogenic carbon is part of the natural carbon cycle. Living trees uptake carbon dioxide from the atmosphere and sequester carbon in the cellular structure of the wood while emitting the resultant oxygen back into the atmosphere. When trees die, they release biogenic carbon, either rapidly during fire events or more slowly during decay. Within this cycle, carbon is sequestered in the forest as living trees, but it can also be exported and sequestered in solid wood products. Our carbon uptake calculations showed that more carbon was exported from the forest per year in even-aged forest management systems (4515 kg/ha-yr) than in uneven-aged systems (3895 kg/ha-yr). The carbon that was exported was stored in long lived wood products as quantified in the findings of Bergman et al. (2013).

The higher yield of wood volume per ha in even-aged systems might reflect greater removal rates than for uneven-aged systems

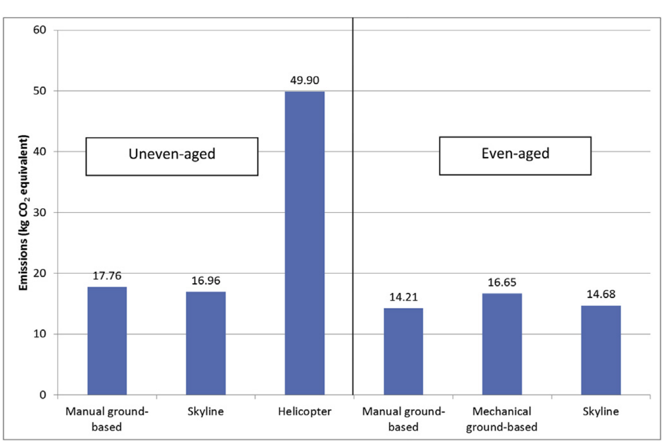

Fig. 3. Greenhouse gas emissions from uneven-aged and even-aged harvest units. This figure shows greenhouse gas emissions from uneven-aged and even-aged harvest units to produce 1-m^3 of redwood sawlogs using three different harvesting and transportation systems each.

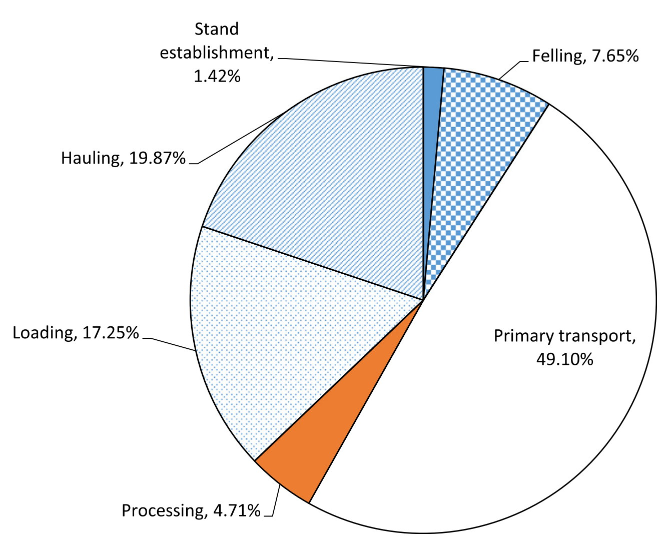

Fig. 4. Relative global warming impacts from each phase. This figure shows the relative global warming impacts from each phase of redwood sawlog harvesting activities.

Table 8
Emissions (kg) to air from logging slash recovery operations and a chip van hauling to an energy plant for a BDmT delivered.

Emissions to air	Total	Feeding	Grinding	Pre-hauling	Loading	Hauling
Aldehydes, unspecified	5.17E-04	2.75E-05	1.41E-04	3.59E-05	2.75E-05	2.85E-04
Ammonia	2.60E-04	1.38E-05	7.09E-05	1.80E-05	1.38E-05	1.43E-04
Carbon dioxide, biogenic	3.01E-02	1.60E-03	8.21E-03	2.09E-03	1.60E-03	1.66E-02
Carbon dioxide, fossil	4.12E+01	2.19E+00	1.12E+01	2.85E+00	2.19E+00	2.27E+01
Carbon monoxide, fossil	3.58E-01	1.90E-02	9.78E-02	2.48E-02	1.90E-02	1.97E-01
Formaldehyde	2.67E-04	1.42E-05	7.29E-05	1.85E-05	1.42E-05	1.47E-04
Hydrogen chloride	3.84E-04	2.04E-05	1.05E-04	2.66E-05	2.04E-05	2.12E-04
Isoprene	7.56E-04	4.02E-05	2.06E-04	5.24E-05	4.02E-05	4.17E-04
Methane, fossil	3.81E-03	2.02E-04	1.04E-03	2.64E-04	2.02E-04	2.10E-03
Nitrogen oxides	7.51E-01	3.99E-02	2.05E-01	5.21E-02	3.99E-02	4.14E-01
Non-methane VOC	2.50E-02	1.33E-03	6.83E-03	1.74E-03	1.33E-03	1.38E-02
Particulates, > 2.5 μm, and <10 μm	2.31E-02	1.23E-03	6.31E-03	1.60E-03	1.23E-03	1.28E-02
Particulates, unspecified	3.94E-03	2.09E-04	1.08E-03	2.73E-04	2.09E-04	2.17E-03
Propene	5.79E-04	3.08E-05	1.58E-04	4.02E-05	3.08E-05	3.19E-04
Sulfur dioxide	2.10E-02	1.11E-03	5.72E-03	1.45E-03	1.11E-03	1.16E-02
Sulfur oxides	4.16E-02	2.21E-03	1.13E-02	2.88E-03	2.21E-03	2.29E-02
VOC, volatile organic compounds	1.97E-02	1.05E-03	5.37E-03	1.37E-03	1.05E-03	1.09E-02
Total	4.24E+01	2.26E+00	1.16E+01	2.94E+00	2.26E+00	2.34E+01
%	100.0	5.3	27.3	6.9	5.3	55.1

during the period covered by this analysis. Over the long term, in forests that are continuously managed for wood production the volume removed per ha must be balanced by growth through sustainable forest management practices. If harvest during the period of study was in line with the growth increment, then the higher yield likely reflected inherent differences in site productivity across our study area and between areas managed using the two silvicultural systems in question. Higher quality sites would produce more volume/ha per year, but site productivity data were not collected as part of this study. A third possibility was that historically regeneration success and growth in the stands managed using an uneven-aged system was lower due to excessive shading (O'Hara and Berrill, 2010) and therefore the volume available for harvest was reduced.

The total emissions related to the production of redwood decking (i.e. cradle-to-grave) including redwood forest management activities were calculated in a separate study (Bergman et al., 2013). Their paper suggested that the emissions from redwood forest management activities for GWP, ozone depletion, smog, acidification, and eutrophication were 14%, 2%, 56%, 75%, and 48%, respectively, of the total cradle-to-grave analysis of redwood decking. It was noted that the environmental impact factors (e.g., GWP and ozone depletion) from the redwood forest management activities were relatively high when compared to the full cradle-to-grave LCA values for other species producing sawlogs. The 14% of GWP impact for the redwood forest management activities component of the cradle-to-grave redwood LCA was higher than for the typical cradle-to-gate mill input values for most other wood product manufacturing LCAs. This was primarily because redwood decking used minimal kiln drying which substantially lowered the cumulative energy consumed during redwood decking manufacturing relative to many other wood products (Bergman et al., 2014). Typically, primary energy consumed in forest management activities is less than 5% of the primary energy consumed during the cradle-to-gate wood product production process (Puettmann and Wilson, 2005; Puettmann et al., 2010) and primary energy use correlates well with the listed impact categories.

5. Conclusions

This was the first study to use LCIA methods to quantify the environment impacts related to redwood forest management practices including stand establishment, intermediate forest treatment, harvesting system profiles, and hauling to supply redwood sawlogs. Redwood is a unique species naturally growing along the coast of northern California. It is well known as a naturally durable material for producing wood decking products and other wood construction materials. Forest management practices to grow redwood trees are somewhat different than other North American conifers due to its unique ability to sprout from stumps, fast growth, and high yield per hectare. However, post regeneration practices found in redwood forests including silvicultural systems (even-aged and uneven-aged) and harvest systems (ground-based, skyline and helicopter) are in other US forests as well.

Previous forest resource harvesting studies showed that timber harvesting activities represented high levels of emissions

Table 9
Impact assessment associated with redwood logging slash recovery operations and hauling with a chip van to energy plant.

Impact category	Unit[a]	Total	Feeding	Grinding	Pre-hauling	Loading	Hauling
Global warming	kg CO_2	4.30E+01	2.29E+00	1.17E+01	2.99E+00	2.29E+00	2.37E+01
Acidification	H+ moles	3.33E+01	1.77E+00	9.09E+00	2.31E+00	1.77E+00	1.84E+01
Carcinogenics	kg benzen	1.53E-02	8.12E-04	4.17E-03	1.06E-03	8.12E-04	8.42E-03
Non carcinogenics	kg toluen	3.18E+02	1.69E+01	8.67E+01	2.20E+01	1.69E+01	1.75E+02
Respiratory effects	kg PM2.5	3.62E-02	1.92E-03	9.88E-03	2.51E-03	1.92E-03	2.00E-02
Eutrophication	kg N eq	3.45E-02	1.84E-03	9.43E-03	2.40E-03	1.84E-03	1.90E-02
Ozone depletion	kg CFC-11	1.74E-09	9.23E-11	4.74E-10	1.20E-10	9.23E-11	9.57E-10
Ecotoxicity	kg 2,4-D	8.82E+00	4.69E-01	2.41E+00	6.12E-01	4.69E-01	4.86E+00
Smog	g Nox	7.75E-01	4.12E-02	2.12E-01	5.38E-02	4.12E-02	4.27E-01
	Total	4.04E+02	2.15E+01	1.10E+02	2.80E+01	2.15E+01	2.23E+02
	%	100.0	5.3	27.3	6.9	5.3	55.1

[a] All units are equivalent to the unit that is stated for each category per BDmT of biomass delivered.

associated with the overall forest management activities. Our study confirmed the study results from other studies that timber harvesting and transportation activities were a major (>90%) contributor to the overall carbon emissions. In addition, we found that primary in-woods transport activities such as skidding and yarding consumed fuels far more than other activities (felling, processing, and loading) in stump-to-truck timber harvesting operations. These results were especially noticeable with helicopter and skyline harvesting systems, compared with ground-based operations. Hauling sawlogs to the sawmill represented the second highest activity of consuming fuels at a 52-km of one-way hauling distance, which would be significantly increased with increase of hauling distance. Further, uneven-aged silvicultural systems resulted in higher fuel consumption compared to even-aged silvicultural systems. The emissions and the resulting environmental impacts associated with different timber harvesting activities and silvicultural systems have not been explicitly documented in other papers. This study shows substantial differences in harvesting operations and silvicultural systems that impact the LCIA of forest management and operations. These differences should be carefully considered when evaluating the environmental performance of forest management choices, both in terms of forest operations and silvicultural systems. For example, when harvesting redwood sawlogs, one could vary the application of even- and uneven-aged silvicultural systems to minimize overall environmental impacts. In addition, this paper provides LCIA results for harvesting redwood sawlogs using helicopters while protecting environmentally sensitive areas and not building roads.

Some other studies often relied on average values obtained for a large region (e.g. western US or the entire US) based on secondary literature sources. However, all the data used for this study represented surveyed results of harvesting productivity and fuel consumption from redwood forest landowners. Because of their specificity, the results from this study need to be carefully evaluated as to their appropriateness for use in other places and forest types. This study did not consider the environmental impacts related to road maintenance and construction or the manufacture of forest harvesting equipment. Including these items would alter the final results presented in this paper and for regions where new infrastructure is needed, these elements would need to be included in the analysis.

Acknowledgement

We gratefully acknowledge the financial assistance for this research project provided by the California Redwood Association.

References

ASTM International, 2010. Standard Practice for Categorizing Wood and Wood-based Products According to Their Fiber Source. ASTM D7612-10. American Society for Testing and Materials, West Conshohocken, PA, pp. 783–793.

ASTM International, 2014. Standard Guide for Evaluating the Attributes of a Forest Management Plan. ASTM D7480-08. American Society for Testing and Materials, West Conshohocken, PA, pp. 787–798.

Bare, J.C., 2011. TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0. Clean. Tech. Environ. Policy 13, 687–696.

Bergman, R.D., Han, H.-S., Oneil, E., Eastin, I.L., 2013. Life-cycle Assessment of Redwood Decking in the United States with a Comparison to Three Other Decking Materials. CORRIM Final Report. University of Washington, Seattle, WA, p. 101.

Bergman, R., Han, H.-S., Oneil, E., Eastin, I., 2014. Life cycle impacts of manufacturing redwood decking in northern California. Wood Fiber Sci. 46 (3), 322–339.

Berrill, J.-P., Deffress, J.L., Engle, J.M., 2012. Coast redwood live crown and sapwood. General Technical Report PSW-GTR-238. In: Proceedings of Coast Redwood Forests in a Changing California: a Symposium for Scientists and Managers. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 473–484.

Bowyer, J., Howe, J., Stai, S., Trusty, W., Bratkovich, S., Fernholz, K., 2012. The International Green Construction Code Implications for Materials Selection in Commercial Construction. Dovetail Partners, Inc, p. 16 (accessed 18.07.14.). http://www.dovetailinc.org/report_pdfs/2012/dovetailigcc0512.pdf.

Cambria, D., Pierangeli, D., 2012. Application of a life cycle assessment to walnut tree (Juglans regia L.) high quality wood production: a case study in southern Italy. J. Clean. Prod. 23, 37–46.

Clark, J.W., Scheffer, T.C., 1983. Natural decay resistance of the heartwood of coast redwood Sequoia sempervirens (D. Don) Endl. For. Prod. J. 33 (5), 15–20.

Dias, A., Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 23, 368–376.

Dicus, C.A., Delfino, K., 2003. Comparison of the California Forest Practice Rules and Two Major Certification Systems. Urban Forests Ecosystems Institute Research Report 10, p. 63.

EPA, 2005. Metrics for Expressing Greenhouse Gas Emissions: Carbon Equivalents and Carbon Dioxide Equivalents. EPA420-F-05-002, p. 3.

EPA, 2012. eGRID2012 Version 1.0 Year 2009 GHG Annual Output Emission Rates. Environmental Protection Agency, United States. http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2012V1_0_year09_GHGOutputrates.pdf.

FPInnovations, 2013. Product Category Rule (PCR): for Preparing an Environmental Product Declaration (EPD) for North American Structural and Architectural Wood Products. UN CPC 31. NAICS 21, p. 17. https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/wood-products-pcr-version-v1.1-may-2013-lastest-version.pdf (accessed 18.07.14.).

Ganguly, I., Eastin, I.L., 2009. Trends in the US decking market: a national survey of deck and home builders. For. Chron. 85 (1), 82–90.

González-García, S., Krowas, I., Becker, G., Feijoo, G., Moreira, M.T., 2013. Cradle-to-gate life cycle inventory and environmental performance of Douglas-fir roundwood production in Germany. J. Clean. Prod. 54, 244–252.

González-García, S., Bonnesoeur, V., Pizzi, A., Feijoo, G., Moreira, M.T., 2014. Comparing environmental impacts of different forest management scenarios for maritime pine biomass production in France. J. Clean. Prod. 64, 356–367.

Handler, R., Shonnard, D., Lautala, P., Abbas, D., Srivastava, A., 2014. Environmental impacts of roundwood supply chain options in Michigan: life-cycle assessment of harvest and transport stages. J. Clean. Prod. 76, 64–73.

ISO, 2006a. Environmental Management—Life-cycle Assessment—Principles and Framework. ISO 14040. International Organization for Standardization, Geneva, Switzerland, p. 20.

ISO, 2006b. Environmental Management—Life-cycle Assessment—Requirements and Guidelines. ISO 14044. International Organization for Standardization, Geneva, Switzerland, p. 46.

Johnson, L., 2008. Harvest Factors Spreadsheets for CORRIM Forest Resources Module: Documentation and User's Guide. Final report presented to CORRIM, p. 21.

Johnson, L., Lippke, B., Marshall, J., Comnick, J., 2005. Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. Wood Fiber Sci. 37, 30–46. CORRIM Special Issue.

Johnson, L., Lippke, B., Oneil, E., 2012. Biomass collection and wood processing life cycle analysis. For. Prod. J. 62 (4), 258–272.

Jones, D.A., O'Hara, K.L., 2012. Carbon density in managed coast redwood stands: implications for forest carbon estimation. Forestry 85, 99–110.

Lippke, B., Comnick, J., Johnson, L.R., 2005. Environmental performance index for the forest. Wood Fiber Sci. 37, 149–155.

Lippke, B., Wilson, J., Meil, J., Taylor, A., 2010. Characterizing the importance of carbon stored in wood products. Wood Fiber Sci. 42, 5–14.

Mahalle, L., O'Connor, J., 2009. Life Cycle Assessment of Western Red Cedar Siding, Decking, and Alternative Products. Final report presented to Western Red Cedar Lumber Association, p. 142.

Miles, P.D., Smith, W.D., 2009. Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America. Research Note NRS-38. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, p. 35.

O'Hara, K.L., Berrill, J.P., 2010. Dynamics of coast redwood sprout clump development in variable light environments. J. For. Res. 15 (2), 131–139.

Oneil, E., Lippke, B., 2010. Integrating products, emission offsets, and wildfire into carbon assessments of Inland Northwest forests. Wood Fiber Sci. 42, 144–164.

Oneil, E.E., Johnson, Leonard R., Lippke, Bruce R., McCarter, James B., McDill, Marc E., Roth, Paul A., Finley, James C., 2010. Life cycle impacts of Inland West and NE/NC forest resources. Wood Fiber Sci. 42, 29–51.

PRé Consultants, 2013. SimaPro Life-cycle Assessment Software Package, Version 7.3. Printerweg 18, 3821 BB Amersfoort, The Netherlands. http://www.pre-sustainability.com/ (accessed 04.02.13.).

Puettmann, M., Wilson, J., 2005. Life-cycle analysis of wood products: cradle-to-gate LCI of residential building materials. Wood Fiber Sci. 37, 18–29 (CORRIM Special Issue).

Puettmann, M., Bergman, R.D., Hubbard, S., Johnson, L., Lippke, B., Wagner, F., 2010. Cradle-to-gate life-cycle inventories of US wood products production – CORRIM Phase I and Phase II Products. Wood Fiber Sci. 42, 15–28 (CORRIM Special Issue).

Puettmann, M., Oneil, E., Milota, M., Johnson, L., 2013a. Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Pacific Northwest. American Wood Council. April 2013. http://www.corrim.org/pubs/reports/2013/phase1_updates/PNW%20Lumber%20final%20May%202013.pdf (accessed 06.12.14.).

Puettmann, M., Oneil, E., Milota, M., Johnson, L., 2013b. Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Southeast. American Wood

Council. April 2013. http://www.corrim.org/pubs/reports/2013/phase1_updates/SE%20Lumber%20LCA%20may%202013%20final.pdf (accessed 06.12.14.).

Puettmann, M., Oneil, E., 2013. Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Inland Northwest. American Wood Council. April 2013. http://www.corrim.org/pubs/reports/2013/phase1_updates/INW%20Lumber%20LCA%20Final%20May%202013.pdf (accessed 06.12.14.).

Puettmann, M., Oneil, E., Bergman, R., Johnson, L., 2013c. Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Northeast-north Central. American Wood Council. April 2013. http://www.corrim.org/pubs/reports/2013/phase1_updates/NENC%20Lumber%20LCA%20final%20May%202013.pdf (accessed 06.12.14.).

Timmermann, V., Diabdiabova, J., 2014. Greenhouse gas emissions from forestry in East Norway. Int. J. Life Cycle Assess. 19, 1593–1606.

US LCI Database, 2012. National Renewable Energy Laboratory. https://www.lcacommons.gov/nrel/search (accessed 04.02.13.).

Wilcox, W.W., Piirto, D.D., 1976. Decay resistance in redwood (*Sequoia Sempervirens*) heartwood as related to color and extractives. Wood Fiber Sci. 7 (4), 240–245.