A Life-Cycle Assessment of Forest Resources of the Pacific Northwest, USA*

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Abstract

Life-cycle inventory (LCI) and life-cycle assessment (LCA) were used to provide quantitative assessments of the environmental impacts of forest management activities that are required to produce feedstock for wood products such as lumber, engineered panels, and pulp. Primary and secondary data were gathered for the Pacific Northwest Douglas-fir region of the United States to produce an attributional LCA that includes planting, growing, and harvesting trees that are destined for use in wood manufacturing. Using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method, under average management conditions, forest operations can expect to generate from 10 to 18 kg CO_2 equivalent (CO_2 eq) per cubic meter (m^3) of logs ready to leave the landing for the manufacturing facility, depending on the amount of forest residues that are piled and burned. This same cubic meter of log plus bark will have sequestered 960 kg CO_2 eq during its growth cycle, for a net greenhouse gas sink of 942 to 950 kg CO_2 eq per m^3. Forest management impacts are from 1 to 13 percent of the total impacts from the cradle to gate for global warming potential and the potential to increase smog, eutrophication, and acidification. Upstream impacts associated with the production of herbicides are reflected in the ozone potential impact category. These LCA results can be used as upstream processes for wood manufacturers interested in developing Environmental Product Declarations for products that use these resources as inputs.

The Consortium for Research on Renewable Industrial Material (CORRIM) has developed research protocols (CORRIM 1998) and methodologies that have been used to conduct a wide range of attributional life-cycle inventory (LCI) and life-cycle assessments (LCA) for forestry operations, manufacturing of durable wood products, and cellulosic biofuels across the United States and North America. CORRIM methodologies were designed to ensure that results are consistent with International Organization for Standardization (ISO) protocols (ISO 2006) and more recently the product category rules (PCR) for North American Structural and Architectural Wood Products (FPInnovations 2015), thus facilitating their use in global assessments and commercial transactions.

In CORRIM's first life-cycle research project, the Pacific Northwest (PNW) LCI of forest resources (Johnson et al. 2005a) was heavily based on secondary data, including modeling of forest growth and yield of representative Douglas-fir (*Pseudotsuga menziesii*) stands in the region. Results from this initial effort were developed into a series of representative harvest scenarios in the context of LCA. Since the original PNW forest resources LCI was published in 2005 (Johnson et al. 2005b), there has been a tremendous focus on the carbon footprint of wood and wood products, not only in the literature, but in the public policy and marketing arenas as well. In 2012 the original 2005 PNW forest resource LCI was updated and expanded to include a life-cycle impact assessment (LCIA; Puettmann et al. 2013) and has subsequently been used to inform environmental

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policy and market transactions, including the development of environmental product declarations for wood products (American Wood Council [AWC] 2013).

In the PNW, forest operations are in a state of continuous evolution in response to regulatory constraints, regional and international economic drivers, and improvements in forest management techniques. Some significant changes include modifications to air quality specifications that limit open burning windows, reduced harvest from public lands, and changes in the ownership patterns on private lands. This project was undertaken to update and expand the Johnson et al. (2005a) report to include information on modified management regimes, yield information, and site treatments that were not available during the initial investigation. In addition, this work includes an LCIA using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method developed by the US Environmental Protection Agency (EPA; Bare 2011).

Given the increasing interest in understanding the nuances of the potential to offset greenhouse gas (GHG) emissions using wood products, a closer look at the assumptions and data quality used for the initial assessment (Johnson et al. 2005a) was warranted. The demand for updated data was heightened by assertions that forests and durable wood products can play a major role in mitigation of carbon dioxide (CO_2) emissions to the atmosphere, but the accounting can be complex and is subject to broad uncertainties that arise because of insufficient or incomplete data.

In general, the accounting can rely on two specific LCA modalities: attributional or consequential LCA. Attributional LCA quantify inputs and outputs that are directly attributable to the production of a specific product and rely on average data and allocation between processes to quantify burdens (United Nations Environment Programme [UNEP] 2011). In contrast, consequential LCA look at alternative scenarios at the margins (i.e., how will producers modify their actions based on changes in external drivers) and rely on system expansion to handle allocation questions (UNEP 2011). With its focus on incorporating average data from suppliers and allocating burdens to processes and outputs, this study clearly fits into the attributional LCA category. As such, the results are suitable for applications that require data on the attributional LCA for sawlogs from the PNW region.

Regional Description

This regional analysis provides estimates of the yield and emissions associated with management of representative timber producing hectares for the area west of the Cascade Mountains in Washington and Oregon in what is commonly called the PNW Douglas-fir region. This region is dominated by temperate coniferous rainforests composed mainly of Douglas-fir and western hemlock (*Tsuga heterophylla*), with other species such as spruce (*Picea* spp.), true firs (*Abies* spp.), and western redcedar (*Thuja plicata*) making up a smaller component of the harvested softwood volume. Owing to its temperate climate, and 75 years of effort directed toward developing techniques that support scientific forest management, this timber-producing region is among the most productive in the world. The climate and productivity advantages of the region are augmented with the presence of a modern and efficient manufacturing and transportation infrastructure, a robust regulatory framework for forest operations and manufacturing, and a long history of forest management on the part of both public and private forest landowners.

Forest landownership is divided among large industrial, large private, small private, tribal, state, county and local government, and federal interests. Despite holding a relatively small percentage of forest area, trends by ownership by state indicate that the largest percentage of timber harvest comes from large industrial and large private land holdings.

In western Oregon, harvests from large private and industrial lands have remained relatively stable for nearly half a century with minor perturbations related to wide-scale economic conditions such as the 2008 financial collapse (Fig. 1). In contrast, harvests from public lands have fluctuated widely and are in a gradual decline in response to environmental litigation, endangered species listings, the Northwest Forest Plan (NWFP 1993), and other pressures for public use of lands that were previously designated for timber production. Harvests from small forest landowners are also stable but provide a relatively small amount of the harvest volume over the long term at an average of 7 percent of the total harvest and 12 percent of the private harvest volume for the state. In Oregon, harvests from large industrial and large private lands have never dropped below 65 percent of the total harvest volume since 1995 and average 88 percent of the total private harvested volume over that same period. Recent analysis (L. W. Rogers, J. C. Comnick, and A. Cooke, unpublished data, 2017) shows that industrial and large private landowners own 33 percent of the unreserved productive forestlands in western Oregon. Since 1994, they have produced 72 percent of the total western Oregon harvested timber from that acreage. This landowner group also holds an additional 6 percent of the forested area, which is classified as reserved forest (i.e., unavailable for harvest). In comparison, small forest landowners hold 20 percent of the productive timberland in western Oregon and harvest 10 percent of the total reported timber volume during the same time period.

In western Washington, harvest on large private and industrial forestland has averaged approximately 61 percent of total timber volume and 83 percent of the volume on private lands since 1965 (Fig. 2). Since the spotted owl (*Strix occidentalis*) was listed under the Endangered Species Act and the NW Forest Plan was implemented in 1993, average harvest levels on private and public lands have declined in lockstep, with the relative percentage of volume removed by each landowner group largely unchanged. Among private landowners there has been a slight shift in the allocation of harvest volume over the period, with small forest landowners now harvesting about 25 percent of the total private timber volume offered for sale, whereas they harvested approximately 17 percent of the private timber volume overall since 1965. Given the predominance of harvests from large private and industrial landowners in the PNW Douglas-fir region, this analysis targeted information on management, yield, and operations of this subset of landowners as representative of the region.

LCA Goal and Scope Definition

The goal of this work was to update and revise energy and material inputs and outputs associated with the production of softwood logs grown in the PNW region of North America. The results can be used as upstream inputs for the

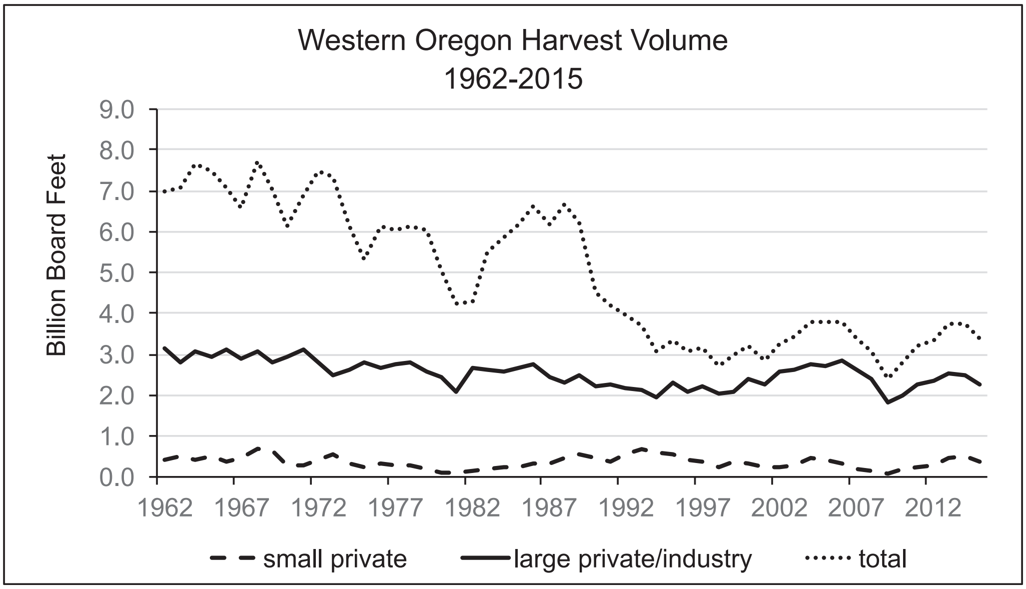

Figure 1.—Timber harvest volume and trends for private landowners relative to total harvest volume, western Oregon. Source: Compiled from data from https://data.oregon.gov/Natural-Resources/Timber-Harvest-Data-1942-2015/v7yh-3r7a/data.

development of attributional LCA for all wood products that are manufactured in the region from softwood logs. The attributional LCA framework quantifies inputs and outputs used in the production of a functional unit of product, in this case a cubic meter of sawlogs destined for a manufacturing facility.

The scope was limited to the evaluation of the inputs and outputs as defined by the system boundary (Fig. 3). It begins with silvicultural operations that include site preparation (preparing the site for planting of new seedlings using herbicides and/or slash piling), planting, and stand management (including herbicide applications and pre-commercial thinning on a subset of hectares) and ends with harvesting operations that include felling (cutting the trees down), yarding (moving the trees to the landing or roadside), processing (cutting the trees into lengths suitable for transport), and loading onto the logging truck, with forest residue management postharvest.

Hauling is reported in this analysis as an average across all types of end products. Hauling is summarized separately to facilitate gate-to-gate analysis for individual manufacturing types that rely on mill surveys to adjust input haul distances that reflect their unique feedstock acquisition regions. Inputs include seedlings, fuel and electricity to grow seedlings, fuel use for site preparation and management, herbicides and their application, and harvesting, including any mid rotation thinning operations. Outputs include emissions related to the production of 1 m^3 of logs

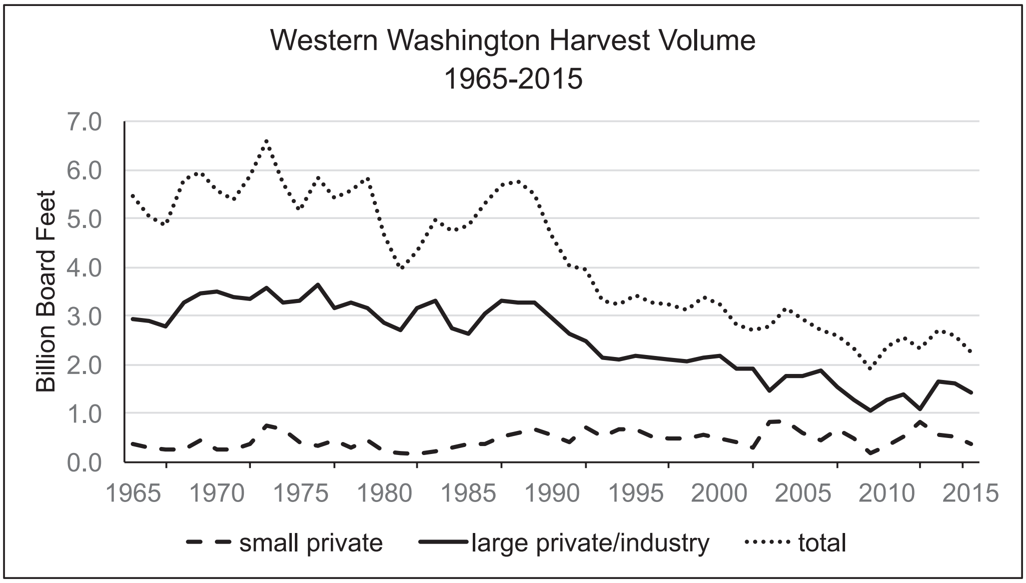

Figure 2.—Timber harvest volume and trends for private landowners relative to total harvest volume, western Washington. Source: Compiled from data from http://www.dnr.wa.gov/TimberHarvestReports.

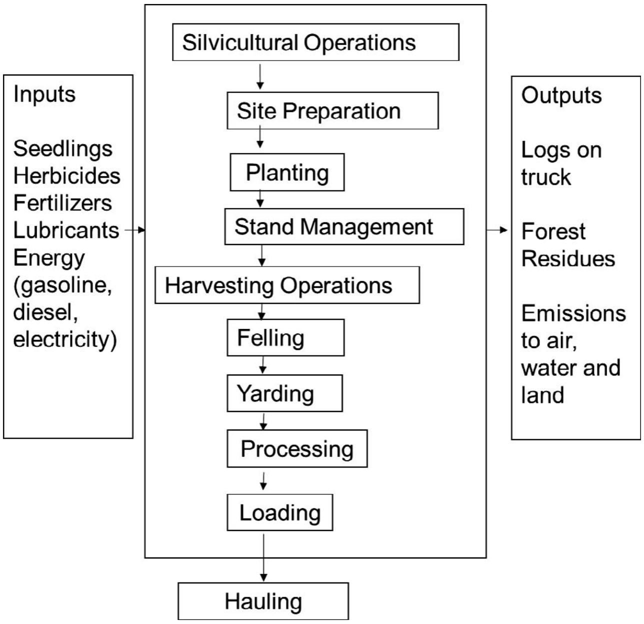

Figure 3.—System boundary for Pacific Northwest forest resources life-cycle assessment.

destined for the manufacturing facility, the logs themselves, and waste including forest residues.

Inputs and outputs are derived based on weighted average values for all production processes. While there can sometimes be removal of residues for use in bioenergy applications, data on that potential recovery activity were not collected or assumed for this analysis. Because there were no coproducts, all burdens were allocated to the logs. The results report burdens for 1 m^3 of logs loaded and ready for transportation to a manufacturing facility. Although logs are transported green, the allocations are based on their oven dry weight per cubic meter.

When trees are harvested, the tops, limbs, damaged, and undersized trees are left as forest residues. These residues can be either left behind to decay in situ, yarded to the landing where they are piled and left to decay, piled and burned, or removed as a source of bioenergy feedstock. If the material is removed from the site as a source of bioenergy, it becomes a coproduct and can be assigned upstream forestry burdens and consequent impacts. That case is outside the scope of this analysis. If the material was left to decay in situ, it was excluded from the analysis as being outside the system boundary. If the material was burned to meet fire hazard abatement regulations, or to increase plantable spots, it generated emissions that were captured in the life cycle and allocated as a burden to the harvested wood volume. Accounting for the amount of residues and producing estimates of the volume that could be burned were included as part of the analysis.

Methods

Data development

A wide range of primary and secondary data sources were used to characterize the cradle-to-gate LCI for the production of a cubic meter of logs in the PNW region. Table 1 identifies data sources and summarizes inputs and outputs per hectare and per cubic meter for all process steps. Detailed descriptions of each input follow and are summarized by management and harvesting activity in subsequent tables.

Forest yield, rotation age, and management systems were based on a combination of primary survey data of forest landowners, literature sources, the Washington State Forest Land Database (Rogers et al. 2012), and evaluation of harvest statistics for the two-state region (Oregon DATAMart 2015, Washington Department of Revenue [WA DOR] 2015). Primary survey data for management and operations were from large industrial and large private landowners for the survey year 2010. Statewide harvest statistics from 2010 were used for comparative purposes. This subsample of forest operations within the region is representative of 65 percent of the total annual harvest volume across the two-state region. In western Oregon, 75 percent of the harvested volume (2010 data) came from large industrial and large private forest landowner holdings. That same year, 53 percent of the harvest volume in western Washington came from this landowner group. Overall, PNW timber harvest was approximately 5 billion board feet (BBF) in 2010, of which 3 BBF (65%) was from industrial and large private land holdings.

Table 2 summarizes data collected to represent the average treatment regime by harvest type for large private landowners in the PNW Douglas-fir region. Commercial thinning operations occur on approximately 14 percent of the forestland that will ultimately be harvested using a ground-based system at year 50, which is equal to 8 percent of the total harvest area. Commercial thinning operations typically occur between the ages of 25 and 35 years depending on site productivity, stand density, tree size, yield, and potential economic return. The ultimate decision to opt for commercial thinning is driven by the interaction of all these variables and is therefore highly variable in timing and extent. For this analysis, a conservative estimate of yield early in the rotation was used as a reasonable scenario given the high harvest volumes reported at year 50.

The allocation of final harvest type between ground-based and cable-based harvest systems is driven by the amount of land that is too steep to safely harvest with ground-based equipment. In this case, for final harvest at year 50, the forest is harvested using ground-based systems 56 percent of the time and cable-based systems 44 percent of the time. Almost always the final harvest removes all but designated reserve trees (wildlife retention trees or green retention trees) in order to facilitate the establishment of a new crop of shade-intolerant Douglas-fir using an even-aged silviculture system.

Volume and yield information in management surveys was reported in the US measurements of thousand board feet (MBF). This system of measures relies on a complex set of rules that vary by region, log diameter, and length (Briggs 1994). To ensure consistency with downstream data uses, the conversion factor used to convert MBF to cubic measure (cubic feet or cubic meters) used for this study was taken from mill survey data for PNW lumber mills (Milota 2015), which reflects the average size of harvested logs entering these mills. Conversion from MBF to cubic meters used a factor of 0.1395 MBF/m^3. Weighted average density was calculated at 464 kg/m^3 (oven dry wood on a dry basis moisture content) based on weighted average specific gravity by species (Oregon DATAMart 2015, WA DOR 2015) and average moisture content of harvested logs

Table 1.—Data sources and amounts for inputs/outputs.

Inputs/outputs	Input/output per ha	Input/output per m^3	Data required for	Data sources[a]	Supporting upstream data	Source
Seedlings (no.)	1,092	2.096	Regeneration	1	Electricity and fertilizer use	2
Herbicides (kg)	4.437	0.009	Site preparation/ release	1	Upstream production processes and emissions	Ecoinvent 3.0
Fertilizers (kg)	71.734	0.138	Stand management	1	Upstream production processes and emissions	US LCI
Gasoline (liters)	109.553	0.210	Stand management and harvest	Calculated from 1 and 2	Upstream production processes and emissions	US LCI
Diesel (liters)	1,588.400	3.049	Stand management and harvest	Calculated from 1, 2, 3	Upstream production processes and emissions	US LCI
Jet fuel (liters)	7.852	0.015	Site preparation and stand management	Calculated from 1	Upstream production processes and emissions	US LCI
Electricity (MJ)	0.000	2.66E−07	For seedling production	2	Upstream production processes and emissions	US LCI
Lubricants (liters)	24.943	0.048	For equipment usage	2, 3	Upstream production processes and emissions	US LCI
Sawlog yield (m^3)	521	1	Output	1		
Residue yield (kg)	68,063	130.6	Waste left to decay or burn	Calculated from sawlog yield using equations from 2		
Emissions from pile burning (see Table 3 for emission by species)			Emissions to air	Calculated from residue yield using equations from 4, 5		

[a] 1 = landowner survey; 2 = Johnson et al. (2005a, 2005b); 3 = Han et al. (2014); 4 = Battye and Battye (2002); 5 = Prichard et al. (2006).

(Milota 2015). Stem yield is always calculated exclusive of bark; therefore, average relationships of bark to stem biomass from Milota and Puettmann (2017) of 12.8 percent were used to calculate bark volume, which was included in total forest residue estimates. Together these factors were used to convert MBF to cubic meters and calculate the volume of logs that could be moved at one time during yarding and hauling operations. These factors were also used to convert the average volume that is removed during harvesting into SI units as shown in Table 2. Volume was allocated between harvest types (commercial thin, ground, and cable harvest) based on primary survey data.

Table 2.—Management and harvest timeline and yield.

Prescription scenarios	Commercial thin	Ground	Cable
Entry period/rotation age	25	50	50
Planting density (trees/ha)	0	1,092	1,092
Fertilization	None	35	None
Precommercial thin	None	Year 15	None
No. of trees/ha	0	741	0
Commercial thin (m^3/ha)	92	0	0
Commercial thin at year	25	0	0
Final harvest (m^3/ha)	0	575	531
Final harvest at year	0	50	50
Total harvest (m^3/ha)	92	575	531
Percent thinned	100	14	0
Average yield (m^3/ha/yr)	4	12	11
Percent land in category, base	8	52	40

Forest management operations and inputs

Table 3 summarizes the management inputs needed to establish crop trees and grow them to harvestable size. It includes per hectare data for inputs needed for planting, site preparation, conifer release, pre-commercial thinning, and fertilization, including fuels needed to apply herbicides and fertilizers and move crews to and from the plantations. Specific details are as follows.

In both Oregon and Washington, forest regeneration following harvest is required by law. Minimum stocking standards (number of trees per hectare) and requirements to protect them from being overtopped by competing vegetation are set forth in the Washington Administrative Code (Washington State Legislature 2005, WAC 222-34-010) and the Oregon Forest Practices Act (Oregon Department of Forestry 2008, 629-610-0020). While regeneration from naturally occurring seed is permitted under these regulatory frameworks, it is not commonly used because the delays in regeneration can be substantial and costly, and this method can result in a failure to adequately reforest the harvest area. Given that large private and industrial landowners are focused on the efficient production of their crops of trees, it also does not make economic sense to forego planting in favor of an uncertain outcome from naturally regenerated

Table 3.—Management inputs (per hectare).

	Planting	Aerial herbicide	Ground herbicide	Fertilization	Precommercial thinning
Seedlings	1,092				
Glyphosate (kg/ha)		2.80	2.80		
Sulfometuron-methyl (kg/ha)		0.13			
Surfactant (liters/ha)[a]		0.03	0.02		
Tank mix H_2O (liters/ha)		93.54	93.54		
Jet fuel (liters/ha)		4.68		12.44	
Diesel (trucks) (liters/ha)	5.16	2.34	7.02	2.34	7.02
Urea (46-0-0) (kg/ha)				448.34	
Chainsaws (liters/ha)					4.21
Percentage of area treated	100	125[b]	28.8	16.0	27.0

[a] Surfactants that are commonly used in combination with glyphosate herbicides contain a mix of nonionic vegetable-based emulsifiers.

[b] 62 percent of area treated for site prep, 63 percent of area treated for release.

stands. Over the past decade, plantation management strategies have moved away from dense planting for early crown closure to a more targeted approach that relies on early weed control, low-density planting, and post planting herbicide applications as required. All harvested acres are planted, with an average planting density of 1,092 trees per ha (442 trees per acre).

Herbicides are used for both site preparation and removal of competing vegetation after planting in conifer release treatments. The most commonly used sequence for site preparation is to pretreat the area using aerial application of herbicides. This treatment scenario is estimated to occur 62 percent of the time on industrial lands. Depending on the level of brush competition over planted seedlings, a second herbicide treatment may occur 3 to 5 years after planting. This second treatment can be via aerial or ground application depending on the level and distribution of brush impacts. Post planting herbicide applications must consider the potential for seedling damage and are therefore designed to target specific brush species and/or areas with the minimum amount of herbicide required to meet efficacy goals. A post planting aerial herbicide treatment on a subset of hectares with heavy weed competition occurs on 63 percent of the hectares. An additional 29 percent of the total acreage is treated with ground-based herbicides as a conifer release method. In total, herbicides are applied an average of 1.25 times per 50 years using aerial methods and 0.29 times using ground methods (Table 3).

A wide range of herbicides are licensed for forestry use in the PNW for both pretreatment and post planting weed control. Over 90 percent of the time a glyphosate formulation, either alone or in combination with a sulfometuron-methyl formulation, is used to control brush (herbaceous or woody weed competitors) prior to planting. The herbicide mix for site preparation typically includes 2.8 kg/ha (2.5 lb/acre) of glyphosate with 0.015 to 0.03 liters/ha (2 to 4 oz/acre) of sulfometuron-methyl plus 93.5 liters/ha (10 gal/acre) of water and a surfactant to ensure the product disperses effectively and sticks to the leaves. For conifer release, herbicide applications assumed only glyphosate as the active ingredient.

Material safety data sheets of surfactants that are commonly used with glyphosate herbicide provide a summary of their chemical constituents listed as a proprietary blend of ethoxylated fatty amine (i.e., some kind of soap), a glycerol acid complex (i.e., some kind of lecithin), polyoxyethylene ether blend, pH adjusting agents, and deposition agents. Because of this lack of data quality with respect to identifying constituents and no way to identify their percent volume/volume of total product, this process was inserted into the LCI as a ''dummy process.'' The total mass of the surfactant per cubic meter is much less than 1 percent of the LCIA per cubic meter of harvested logs, so this omission is considered of minor significance to the overall LCI and assessment performance.

Older stand management cooperative survey data indicate that the application of urea fertilizer is used on approximately 16 percent of the area, but this is likely an upper bound estimate owing to its high cost. Urea fertilizer is used at up to 448 kg/ha (400 lb/acre) and is distributed using aerial methods (Table 3).

Owing to higher planting densities that occurred 15 to 35 years ago, pre-commercial thinning occurs over 27 percent of the area (Table 3). This practice is expected to decline in the future except for in wetter coastal regions that typically experience significant ingress of naturally regenerating trees.

Harvesting operations

The allocation of harvest systems was obtained from primary survey data and indicates that most of the area is harvested using ground-based systems (8% from commercial thinning, 52% at final harvest; Table 2).

Harvest operations can use a wide range of equipment configurations depending on terrain, volume, piece size constraints, and prescription requirements. Primary survey data indicated that ground-based systems typically used a feller-buncher to cut the trees, a shovel for yarding, and a processor to cut trees to the appropriate merchandizing length at the landing or roadside. For commercial thinning operations where damage to the residual standing trees needs to be minimized, the equipment is smaller and usually will rely on a cut-to-length processing/cutting head. Loading typically requires a large loader at the landing for ground-based final harvests. For low volume commercial thinning operations, a self-loading truck may be used in place of a loader. However, for commercial thinning operations reported in this analysis, it was assumed that a small loader was used at the landing rather than a self-loading truck. For harvesting on very steep slopes, the equipment configuration is substantially different. In these cases, cutting relies on manual felling with yarding done by a cable or skyline system. Trees are either felled and bucked to length in the woods with minimal processing at the landing, or they can be whole-tree yarded to the landing and processed to the appropriate size there. For this analysis it was assumed that trees were yarded to the landing without in-woods bucking and processed on the landing.

No primary data using time motion studies or similar methods were collected for this project. Productivity data for forest harvesting operations were based on logging equipment and equipment configurations developed in spreadsheet models used by Johnson et al. (2005a) and Han et al. (2014) and cross validated to primary survey data for the suite of available equipment options and sizes that are commonly used in the PNW Douglas-fir region (Table 4). Fuel consumption rates were aggregated to produce per cubic meter by harvest type rates as inputs into the LCI. Final fuel consumption rates are based on the allocation of total volume harvested using each harvest system to arrive at an average fuel consumption per cubic meter for the region. Fuel consumption for crew transport to conduct harvest operations was calculated from average haul distance, fuel efficiency of common vehicle types (4 × 4 trucks), and equipment productivity estimates (cubic meters per day per operation). Two-person crews per vehicle were assumed.

Because of fire hazard abatement laws, some areas require postharvest treatment, which includes burning slash at the roadside or landing. Historically, broadcast burning was used to reduce fire hazard and prepare the site for planting. However, it is no longer a common silvicultural practice in the PNW owing to constraints on timing related to air quality indicators, smoke management, and fire hazard conditions. It has been included in this analysis only to provide a retrospective view of the impacts of changing practices on the overall environmental footprint of forest operations over time.

There are large uncertainties in the estimates of forest residues that remain after harvest operations. The following assumptions were used to calculate forest residue volume and mass for the two fire hazard abatement scenarios: herbicide plus pile and burn, and broadcast burn. Harvested logs were cut from the roots approximately 30 cm from the ground. The merchantable part of the log was from the first cut of the stem up to a minimum diameter of 10 to 15 cm (4 to 6 in.) depending on markets and harvest specifications. The tops include all stem parts that were smaller than the minimum diameter, plus branches. Decay, waste, and breakage (DWB) included everything within the merchantable part of the log that cannot meet minimum length or quality specifications because it was decayed, too short, or broken during operations. For PNW final harvest operations utilization was high, so DWB was typically in the 5 to 10 percent range. For commercial thinning operations, DWB is typically higher because of the operational constraints of moving between standing trees and having to remove non-merchantable trees in the path of the machinery. Default values of 20 percent DWB for commercial thinning and 5 percent for final harvests were used for this analysis. The total volume of forest residues therefore comprises the DWB and the tops. Mass of forest residues is calculated based on modeled relationships between stem, bark, roots, and crown biomass using Browne (1962), as these equations were found to provide the best residue to stem relationship for PNW Douglas-fir forests, based on surveys conducted for the Washington Biomass Assessment (WABA; Perez-Garcia et al. 2012).

Table 4.—Harvesting inputs (per cubic meter).

System	Fuel consumption (liters/m^3)	Lubricant consumption (liters/m^3)
Commercial thinning (cut-to-length processor, skidder, loader)	2.372	0.043
Ground-based harvesting (feller-buncher, shovel yarder, slide boom processer, loader)	3.172	0.057
Cable-based harvesting (hand felling, skyline, cut-to-length processor, loader)	3.029	0.055
Weighted average, ground harvesting systems	3.062	0.055
Overall weighted average, all harvest systems	3.051	0.055
Weighted average, crew transport all harvest operations	0.210	0.0016

If fire is used, not all residues are burned because not all forest residues make it to the landing. Data from WABA surveys (Perez-Garcia et al. 2012) and modeling suggest a maximum of 68 percent of the residues will be yarded to the landing. These factors taken together result in estimates of 42.3 to 48.8 metric tons per ha of residues that reach the landing during cable- and ground-based final harvests, respectively. This amount would be equal to 1.6 to 1.8 fully loaded logging truckloads per ha if the residues could be loaded on a logging truck. Open burning does not result in complete combustion; therefore, it was assumed that approximately 90 percent of the total biomass would be consumed when piles were burned. For broadcast burning, 65 percent of total residues are assumed to combust (Prichard et al. 2006).

There are also high levels of uncertainties in calculating emissions from open burning. Best available data from the literature (Battye and Battye 2002, Prichard et al. 2006) were used to calculate emissions from burning forest residues that have either been piled or are consumed during a broadcast burning. The emission profiles cover a range of chemical species including particulate matter (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane hydrocarbons (NMHC), elemental carbon, organic carbon, oxides of nitrogen (NO_x), ammonia (NH_3), volatile organic carbon (VOC), sulfur dioxide (SO_2), methanol, and formaldehyde. Some of the factors are constants and some rely on a number of coarse scale relationships that vary depending on burn stages (flame, smolder, and residual). Taken together, these variables were used along with assumptions about total fuel consumption, the ratio of fine to coarse materials, and total material available, to arrive at emission factors that reflect probable air quality impacts from either of these open burning activities as shown in Table 5.

Haul distances and ancillary data are based on data from the Washington State Log Truck Survey (hereafter log truck study; Mason et al. 2008), which has been cross checked and validated with private forest industry surveys, published literature sources, and the Washington State Biomass Calculator (Rogers et al. 2012) database. The log truck study (Mason et al. 2008) contains data on average haul distances, productivity, mileage, and efficiency of the

Table 5.—Emissions from wood combustion during pile and broadcast burning.[a]

Air emissions (g/kg of dry wood)	Piled slash		Broadcast burn	
	Ground-based harvest	Cable-based harvest	Ground-based harvest	Cable-based harvest
PM	15.18	15.15	26.37	26.41
PM_{10}	4.40	4.41	18.38	18.43
$PM_{2.5}$	3.90	3.91	8.42	8.50
CO	65.25	65.56	194.85	196.13
CO_2	1,687.12	1,686.44	3,290.86	3,288.53
Methane	4.54	4.57	6.32	6.36
Nonmethane hydrocarbons	4.08	4.09	4.88	4.90
Calculated decimal percent	0.96	0.96	0.94	0.94
Elemental carbon	0.28	0.28	0.61	0.61
Organic carbon	2.11	2.11	4.55	4.59
NO_x	2.50	2.50	2.50	2.50
Ammonia	0.48	0.48	1.42	1.43
VOC	5.55	5.57	16.56	16.67
SO_2	0.83	0.83	0.83	0.83
Methanol	0.65	0.65	1.93	1.94
Formaldehyde	1.04	1.05	3.12	3.14

[a] PM = particulate matter; CO = carbon monoxide; CO_2 = carbon dioxide; NO_x = oxides of nitrogen; VOC = volatile organic carbons; SO_2 = sulfur dioxide.

trucking fleet in Washington State. These data were used as a proxy for the entire PNW Douglas-fir region.

Unlike other transport vehicles in the US LCI database (National Renewable Energy Laboratory [NREL] 2012), log trucks carry a payload in only one direction from the forest to the milling facility. They also travel on poor quality gravel roads for a portion of the haul distance, which results in low average travel speeds and low effective mileage rates. Mason et al. (2008) found that 17 percent of the haul distance in western Washington is on gravel roads. Average fuel efficiency from the log truck survey was calculated at 2.17 km/liter (5.1 mi/gal). Average haul distance from the landing to the drop location (manufacturing facility or export yard) was calculated at 104 km (Mason et al. 2008), which is nearly identical to the haul distance from primary survey data for this study (107 km) and near the value for lumber production in the PNW of 108 km (Milota and Puettmann 2017).

Forest management and harvesting data described above were aggregated, weighted to reflect allocation among treatment types, and converted to metric units for input into the SimaPro software package (version 8.3.0.0; Pré Consultants 2012), which was used to conduct the LCI and LCIA. Upstream data needed for the LCI were generated using emission factors for fossil fuel use (diesel, jet fuel, and gasoline), chemicals (herbicides and fertilizers), and electricity based on upstream flows from the US LCI database and Ecoinvent 3.0 databases within SimaPro 8.3.0.0. Ecoinvent databases were updated to reflect US electrical grid, fuel, and chemical values where such data were available and applicable. Ecoinvent databases used the system model ‘‘allocation, default units’’ consistent with the attributional LCA approach taken in this study. The LCIA was generated using the TRACI method (version 3.02, updated 2009; Bare 2011). The TRACI method excludes emissions of biogenic carbon dioxide and biogenic carbon monoxide to the air consistent with the current US approach that treats biogenic carbon dioxide emissions as carbon neutral (Government Printing Office 2016). Results were generated using both this standard approach and a modified approach that uses the TRACI method with biogenic CO_2 emissions included for comparative purposes.

Results

Life-cycle assessment

Using data values and allocations as identified in Tables 2 and 3, an LCI was completed on a per hectare basis for forest management activities. That per hectare value was converted to a per cubic meter value based on the total harvested volume per hectare to generate an attributional LCIA for forest management activities as shown in Table 6. Relative contributions to each of five reported impact categories (ozone depletion, global warming potential [GWP], acidification, eutrophication, smog) and fossil fuel use are shown for the main processes that occur during forest management operations in Figure 4.

Table 7 provides the LCIA for selected impact categories for forest management, harvesting operations, hauling, and alternatives that include herbicide use only or herbicide plus burning forest residues on the landings. These two alternatives are routinely chosen as site preparation techniques with the choice depending on a number of risk variables. The risk variables pertain to the potential for fire to start at the landing after harvest if no fire hazard abatement occurs, the amount of residue that remains on site, public access to the site, whether or not a burn could be conducted safely while meeting air quality objectives, and overall fire hazard abatement goals. While fire is a useful silvicultural tool to manage excess debris, fire risk, and clear planting sites, increasing regulatory limits have constrained its use over time.

Table 8 expands on this issue of fire emissions potential by including broadcast burning. Broadcast burning involves establishing a fire line around the harvest unit and then burning the entire area to reduce slash cover and/or deep organic layers, increase the number of plantable spots, reduce weed invasion, and sometimes to control disease or insect problems. Broadcast burns can be ignited using ground crews or helicopters for aerial ignition. Aerial ignition was modeled in this analysis. While broadcast burning replicates the impact of a wildfire in many ways, there is less material to burn on the site, and the fire is not started until weather and fuel conditions provide a reasonable chance of controlling the outcome. This site preparation practice is no longer regularly used because of concerns over air quality impacts and because of the regulatory requirements to retain standing live trees within harvest units to meet long-term ecological functions. It is included here as a historical reference only. Figure 5 compares the impacts for the three site preparation alternatives across the five impact categories and fossil fuel use.

Biogenic carbon

In Tables 6, 7, and 8, the default TRACI method for calculating GWP is used. Within the TRACI model, biogenic carbon dioxide emissions are not counted as a contribution to GWP (Bare 2011). In order to override this model architecture, the TRACI model was modified to count

Table 6.—Forest management contribution for Pacific Northwest resources including planting, site preparation, weeding, and fertilization per cubic meter.[a]

Impact category	Unit	Total	Herbicide treatments, site prep and release	Seedlings	Fuel use for site prep, planting, fertilization, PCT, and release	Nitrogen fertilizer
Global warming potential	kg CO_2 eq	5.697E−01	8.751E−02	8.495E−02	1.279E−01	2.694E−01
Acidification potential	kg SO_2 eq	5.995E−03	6.382E−04	8.371E−04	1.769E−03	2.750E−03
Eutrophication potential	kg N eq	1.072E−03	8.851E−04	5.331E−05	1.058E−04	2.732E−05
Smog creation potential	kg O_3 eq	8.053E−02	5.320E−03	1.541E−02	5.618E−02	3.600E−03
Ozone depletion potential	kg CFC-11 eq	1.307E−08	1.295E−08	2.366E−12	5.269E−12	1.063E−10

[a] Site prep = site preparation; release = post planting herbicide treatments to remove competing vegetation; PCT = pre-commercial thinning; CFC = chlorofluorocarbon.

biogenic CO_2 as a contributor to GWP in order to generate the comparative analysis in Table 9, which includes biogenic CO_2 as an emission to air. These emissions are then compared with the CO_2 uptake of the harvested logs plus forest residues that are left on site (poor quality stems, root, and crown) for a broader evaluation of the GWP impacts of forest harvesting.

Discussion

Compared with Johnson et al. (2005a), the current analysis includes the following changes: chemical site preparation and brushing, combustion of piled forest residues, lower planting densities, fewer pre-commercial thinning and fertilizer operations, a different mix of harvest systems, and different yields per hectare. These changes to input values were expected to result in changes to the LCA output, but the magnitude and direction of the changes were unknown given how many differences there were in the analysis. In addition, the differences in LCIA results are not directly comparable given that Johnson et al. (2005b) reported only LCI results and used a different LCIA impact methodology to arrive at an impact assessment with a dimensionless value. Comparable results can be derived from the Puettmann et al. (2013) LCA results, which relied on the Johnson et al. (2005b) data to derive forest resource LCA data for the PNW Douglas-fir region.

From the CORRIM guidelines (Puettmann et al. 2014 as updated from CORRIM 1998) it is known that the forest resources contribution does not include hauling to the milling facility because that process is captured in the manufacturing LCA. Puettmann et al. (2013) lists 9.41 kg of carbon dioxide equivalent per cubic meter (kg CO_2 eq per m^3) as the forest resources contribution to the GWP for planed dry PNW lumber. Puettmann et al. (2013) uses the same TRACI method that was used to generate Tables 6 to 8. It takes 1.99 m^3 of logs per cubic meter of planed dry lumber according to mass allocations in Puettmann et al. (2013). Therefore the Johnson et al. (2005a) GWP is

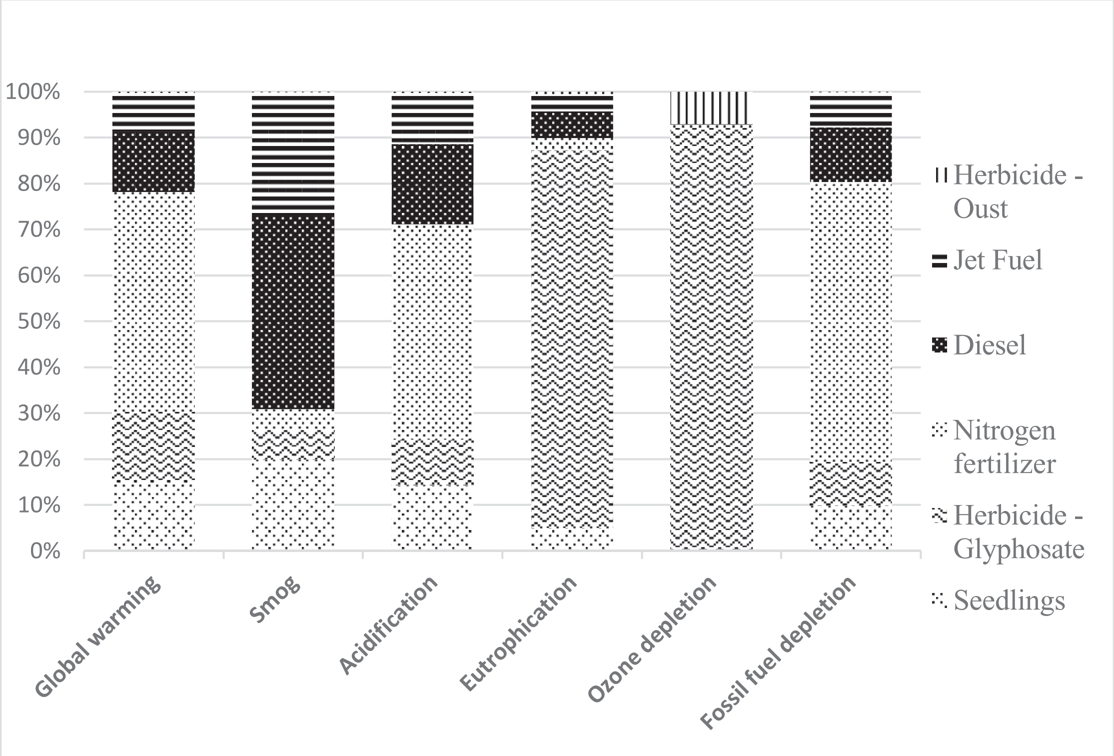

Figure 4.—Relative process contributions by stand management activity (per cubic meter).

Table 7.—Per cubic meter impacts for selected impact categories: forest management, harvesting, hauling, and standard alternative practices.

Impact category	Unit[a]	Forest management	Harvest and load	Total without pile burning	Pile burning emissions	Pile burning equipment use	Total with pile burning	Hauling average distance
Global warming potential	kg CO_2 eq	0.570	10.167	10.736	7.395	0.011	18.142	9.425
Acidification potential	kg SO_2 eq	0.006	0.139	0.145	0.254	0.000	0.400	0.059
Eutrophication potential	kg N eq	0.001	0.008	0.009	0.012	0.000	0.022	0.003
Smog creation potential	kg O_3 eq	0.080	4.415	4.496	5.863	0.004	10.363	1.537
Ozone depletion potential	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total primary energy consumption	MJ	1.233	20.166	21.399	0.000	0.025	21.424	20.790

[a] CFC = chlorofluorocarbon.

estimated at 18.8 kg CO_2 eq per m^3 (1.99 × 9.41) of logs at the landing. This value is higher than either GWP value reported in this study for herbicide-only treatments of 10.74 and 18.14 kg CO_2 eq per m^3 for herbicide plus pile and burn operations. Sonne (2006) report 8.6 Mg/ha CO_2 eq for forestry operations in the PNW region or 8.33 kg CO_2 eq per m^3 based on an average yield of 700 m^3/ha. Based on the average yield of 521 m^3/ha in this study, that same value would represent approximately 16.5 kg CO_2 eq per m^3 of sawlogs. These results indicate that despite all the differences in management activities and variations on input values between these three reports, the overall GWP impacts are substantially similar.

For comparison with roundwood studies from further afield, de la Fuente et al. (2017) found a GWP of 0.23 kg/m^3/yr for plantation-grown Douglas-fir in Germany. The yields predicted in that study were 80 to 110 percent more than the average yield in the PNW, but when converted to a 50-year rotation, the GWP for German Douglas-fir is 11.5 kg/m^3, or slightly more than the lower bound estimate in this study. Gonzalez-Garcia et al. (2013) found a climate change impact of 2.35 kg CO_2 eq per m^3 of roundwood for Douglas-fir grown in Germany, but the assumptions on utilization and yield were very different from those used in this study. For harvesting operations to produce roundwood in Michigan, Handler et al. (2014) found a GWP of 35.7 kg CO_2 eq per dry tonne of biomass. Converting dry tonnes to cubic meters for Douglas-fir at 464 kg/m^3 gives a comparable value of 16.6 kg CO_2 eq per m^3, which is higher than the value found in this study without burning residues. It is consistent, however, with expected emission profiles for areas that use partial cutting silviculture systems. Han et al. (2014) found similar increases in GWP for areas where thinning was used as a harvest method, relative to those areas where clear-cut operations were conducted as they were in this study.

In the PNW Douglas-fir region, there was significant interest in quantifying the potential environmental impacts of herbicide applications. For this study, data were developed using the Ecoinvent 3.0 database for the two most commonly used herbicides, with modifications to upstream energy and chemical inputs to reflect US source data. Emissions to produce and apply herbicides are reported, except for emissions associated with the production of surfactants because of a lack of upstream data and their low percent contribution to the overall system. Over a 50-year rotation, total application rates of the dominant herbicide (glyphosate) are equal to 8.23 g/m^3 of wood, with

Table 8.—Comparative per cubic meter impacts for site preparation alternatives including herbicide only, herbicide plus pile and burn, and broadcast burn using standard TRACI impact indicators.

Indicator	Unit[a]	Herbicide treatment only	Herbicide plus pile and burn treatment	Broadcast burn treatment only[b]
Global warming potential	kg CO_2 eq	10.74	18.14	23.16
Acidification potential	kg SO_2 eq	0.15	0.40	0.61
Eutrophication potential	kg N eq	0.01	0.02	0.03
Smog creation potential	kg O_3 eq	4.50	10.36	18.05
Ozone depletion potential	kg CFC-11 eq	1.35E−08	1.35E−08	5.40E−10
Total primary energy consumption	MJ	21.40	21.42	21.22
Nonrenewable fossil	MJ	21.49	21.42	21.22
Nonrenewable nuclear	MJ	3.19E−08	3.19E−08	3.19E−08
Renewable (solar, wind, hydroelectric, and geothermal)	MJ	8.89E−08	8.89E−08	8.89E−08
Renewable (biomass)	MJ	3.69E−09	3.69E−09	3.69E−09
Material resources consumption				
Nonrenewable materials (fossil fuels)	liters	3.32	3.33	3.29
Renewable materials[c]	kg	−523.84	−523.84	−523.84
Fresh water	liters	0.28	0.28	—
Waste (forest residues)	kg	130.64	130.64	130.64

[a] CFC = chlorofluorocarbon

[b] Broadcast burning is no longer a common practice; for historical reference only.

[c] Sawlogs are created from this process; therefore, the renewable materials value is negative (464.28 kg/m^3 of wood plus 59.56 kg/m^3 of bark = 523.84 kg/m^3 of sawlog).

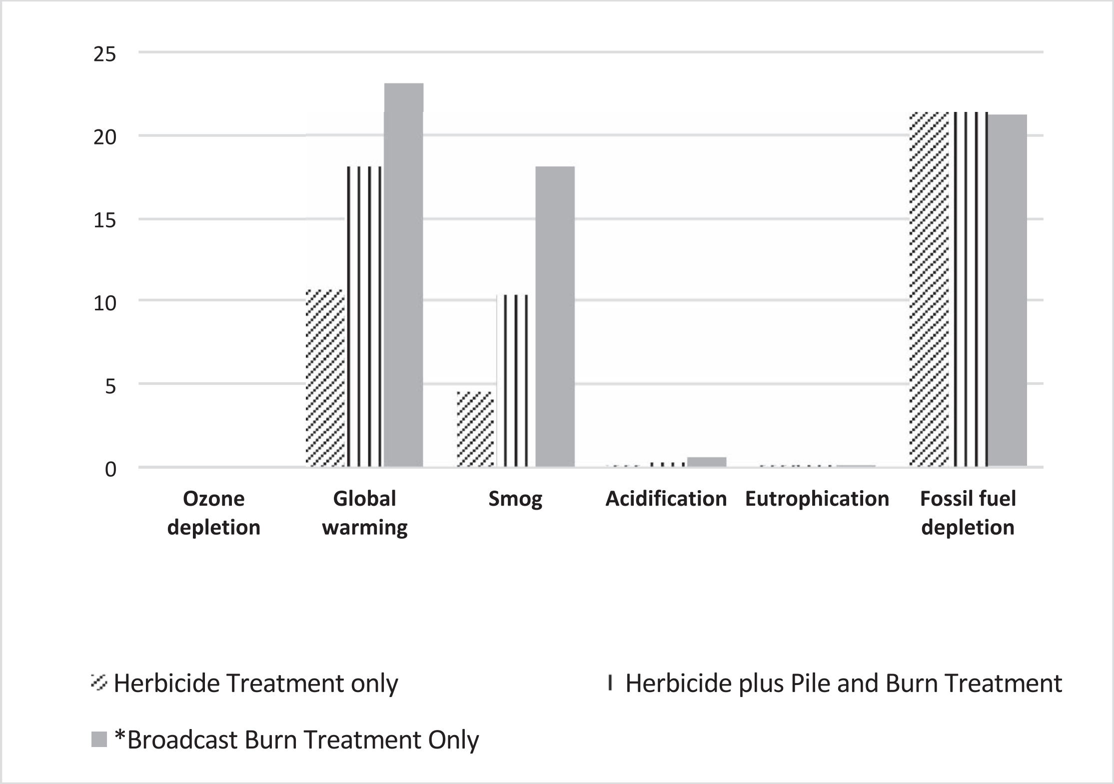

Figure 5.—A comparison of cradle-to-gate impacts by process (per cubic meter).

a total of 9 g of herbicide applied per cubic meter of wood produced. The herbicide represents less than 0.002 percent of the total flow in the production of 1 m^3 of wood with a mass of 523.8 kg (wood plus bark). Despite the small amounts of herbicide that are used, they do represent nearly 100 percent of the ozone depletion potential and over 80 percent of the eutrophication potential (Fig. 4) of management operations. Inspection of the LCI data shows that these impacts are largely a result of upstream processes that occur outside the forested environment, and they are equivalent to only 1.5×10^{-08} kg chlorofluorocarbon **(**CFC-11**)** and less than 0.001 kg N for eutrophication potential.

During forest management operations, the largest contributors to smog potential arise from combustion of diesel and jet fuel (Fig. 4), but these impacts are small compared with the overall impact from harvest operations, with relative impacts of 0.080 versus 4.49 kg O_3 per m^3 of wood produced (Table 7). Likewise, acidification potential from forest management operations is small (0.006 kg SO_2 eq per m^3) at less than 4 percent of the impact from harvest operations without site preparation (Table 7) and approximately 1.5 percent of the impact when pile burning is conducted as a postharvest slash abatement activity.

Nitrogen fertilizer production is responsible for 61 percent of the fossil fuel depletion for forest management activities (Fig. 4), but overall fossil fuel depletion from forest management activities represents less than 6 percent of the total fossil fuel use from cradle to gate for the production of PNW sawlogs (Table 7).

Table 7 quantifies impacts for forest management, harvesting, and postharvest slash abatement by piling and burning. Slash abatement, i.e., the reduction of fire risk by burning slash piles, does not occur on all sites. Thus, Table 7 can be used to represent the lower and upper bound of average impacts to produce 1 m^3 of sawlogs from cradle to grave in the PNW region, with the ‘‘Total without pile

Table 9.—Comparative per cubic meter impacts for site preparation alternatives including herbicide only, herbicide plus pile and burn, and broadcast burn using modified TRACI impact indicators to include biogenic emissions in global warming potential.[a]

Impact category	Unit	Herbicide treatment only	Herbicide plus pile and burn treatment	Broadcast burn treatment only[b]
Global warming potential	kg CO_2 eq	10.75	141.31	315.83
Acidification potential	kg SO_2 eq	0.15	0.40	0.61
Eutrophication potential	kg N eq	0.01	0.02	0.03
Smog creation potential	kg O_3 eq	4.50	10.36	18.05
Ozone depletion potential	kg CFC-11 eq	1.35E−08	1.35E−08	5.40E−10
Fossil fuel depletion	MJ	21.40	21.42	21.22

[a] TRACI = tool for the reduction and assessment of chemical and other environmental impacts; CFC = chlorofluorocarbon.

[b] Historical reference only.

burning'' column representing the lower bound of potential impacts and the ''Total with pile burning'' column representing the upper bound. These impact categories use the standard TRACI methodology, which excludes biogenic CO_2 emissions but includes biogenic methane emissions in the calculation of GWP. If we assume that the forest estate has a stable carbon storage capacity, we can calculate the net GWP emissions per cubic meter of sawlogs as the difference between the total GWP reported in Table 7 less the amount sequestered in the sawlog. One cubic meter of sawlogs in the PNW, including bark, is estimated to contain 960.4 kg CO_2 eq. This value is derived from an average density of 464.28 kg/m^3 of wood plus 59.56 kg/m^3 of bark × 50 percent carbon content × 44/12 as the stoichiometric relationship between C and CO_2. Thus the net GWP for the production of a sawlogs ranges from 942.2 to 949.6 kg CO_2 eq per m^3 of logs loaded on the truck ready for transport to the manufacturing facility.

Table 9 uses a modification to the TRACI method (Bare 2011) that ensures that biogenic CO_2 emissions are counted toward GWP. This modification only has measurable impacts on the slash burning processes because there is negligible biomass burning in any of the upstream processes. As expected from using this modified method, there is a substantial increase in the GWP for the pile and burn and broadcast burn alternatives. Using this modified TRACI method results in an increase of 123 to 293 kg CO_2 eq per m^3 in GWP over the standard TRACI method for pile and burn and broadcast burning slash abatement scenarios, respectively. If these emissions are included, the CO_2 equivalent uptake in the tops and residues that make up that slash are also included in the accounting framework. Browne (1962) equations allocate 68.3 percent of the total tree biomass to the stem, 12.1 percent to the crown, and 19.6 percent to the roots. Using these biomass allocations and an average moisture content of 45 percent, total dry biomass (stem, root, crown) is calculated at 497,141 kg/ha. Volume combusted in the pile and burn operations is calculated at 38,058 kg/ha for a net residual biomass of 459,083 kg/ha after harvest, which includes merchantable volume loaded on the trucks plus unburned forest residues. Allocating the net residual biomass to 521 m^3/ha and converting to kg CO_2 eq gives 1,615 kg CO_2 eq per m^3 of harvested wood products. Adding in the total volume and accounting for the remaining unburned residues and roots results in an increase in the GHG sink for the harvested log to 1,474 kg CO_2 eq per m^3 $\{1{,}615 - (123 + 18)]$ kg CO_2 eq per $m^3\}$. Regardless of method, there is a substantial net GHG sink attributable to the production of 1 m^3 of Douglas-fir logs in the PNW region. This sink is carried forward into manufacturing and can be used to support climate mitigation efforts. These results are useful for quantifying the GWP or carbon footprint of logs, but assertions regarding carbon debt and/or carbon dividend attributable to forest operations require landscape level assessments that are outside the scope of this article.

Data quality

The forest management systems and yield modeled as representative for the PNW Douglas-fir region represent average conditions for industrial and large private landowner management regimes. For the 2010 data reference year, large private and industrial owners harvested an average of 65 percent of the total harvest volume in the region. That volume was removed from a landownership base that represents 36 percent of the total forested hectares in the PNW. Other owner groups harvested at much lower intensities and would therefore have a different, and probably higher, footprint per cubic meter than is reported here. For example, Han et al. (2014) found that in intensively managed even-aged forests in Northern California, forest management and harvesting operations use 20 percent less fuel per equal volume than those managed under a less intensive regime. This result is expected and reflects differences in operational efficiency that arise when harvesting larger volumes of wood per unit area of forest in a shorter time frame. This shift in fuel use has a direct impact on the overall LCA result because fuel consumption is a significant driver in the LCIA results.

Three independent sources of hauling data (log truck study, primary survey data, and Rogers et al. 2012) provide close agreement on average haul distance (97.6 to 107.4 km or 61 to 67.4 mi) for moving sawlogs from the harvest site to the manufacturing facilities in the PNW. Two sources of proprietary primary data for management activities were compared for inclusiveness of activities and percent treatment area relative to the entire area under management. The variances in reported treatment area per year relative to harvested area are consistent and are representative of the average management regime identified within this article. One of the more interesting observations is that results that include primary survey data and an array of management alternatives were found to be consistent with the outcomes from the secondary (modeled) data from Johnson et al. (2005a). They are also in close agreement with the outcomes from Sonne (2006), which looked at a much wider array of management alternatives for the same region.

The semi-quantitative approach to data quality recommended in the product environmental footprint guide (Manfredi et al. 2012) and required by the North American PCR was used to evaluate parameters relating to (1) completeness, (2) methodological appropriateness and consistency, (3) time representativeness, (4) technological representativeness, (5) geographical representativeness, and (6) parameter uncertainty. With that rating system, data are estimated as good quality with an overall score of 2.6 based on rankings of 1, 2, 1, 1, 1, 2 for the six parameters, respectively.

Study limitations

One of the criticisms of prior forest resource LCA studies, and wood LCA studies in general, is the lack of reporting on any meaningful impact indicators related to landscape level impacts of forest harvesting. Evaluation of landscape level impacts of forest operations, including potential impacts to overall forest carbon and biodiversity, are beyond the scope of this analysis. The scope limitation arises for three reasons: (1) there is an inherent scale mismatch that arises when endeavoring to assign landscape level impacts to a functional unit that also makes sense from a wood utilization perspective; (2) the time dimension of harvest affects the overall evaluation of the system; and (3) these results will ultimately be used as inputs for wood manufacturing LCA that are defined on a per unit volume basis, so assessing landscape level impacts would make the two studies incompatible.

An analysis of the challenges of assessing biodiversity impacts of timber harvest can be used to illustrate the scale mismatch issue identified in reason 1 above. Bunnell and Houde (2010) conducted an extensive review of biodiversity markers relevant to PNW forests, with an emphasis on examining the relationships between downed wood and forest dwelling vertebrates along with more general observations about biodiversity of vascular plants and other species (invertebrates, fungi, mosses, liverworts, and lichens). They report two critical aspects of biodiversity that can only be monitored and assessed at the landscape level. First, biodiversity depends as much on what is left behind as it does on what is taken. Bunnell and Houde (2010) report that in order to maintain biodiversity while conducting timber harvests it is necessary to sustain 50 percent of the naturally occurring amounts of downed wood at the landscape level. This means that the need to maintain specific amounts of forest residues postharvest or specific size classes of residues does not depend on the harvest unit but on its relationship to other harvest units in the landscape. The complexity of the task is magnified by challenges in defining the appropriate size for a landscape because that can depend on the home range of the species in question. Overall Bunnell and Houde (2010) conclude that biodiversity cannot be assessed at the scale of a single cubic meter, a hectare, or even a harvest unit of 5, 10, 50, or even 200 ha because it is measureable only at much larger scales—typically at a fifth-order hydrologic unit (HU). In the PNW, a fifth-order HU is approximately 5,200 ha or larger (Mellen-McLean et al. 2009). Any evaluation of harvest impacts at this level requires an integrated economic and supply model framework that is outside the scope of attributional LCA studies.

This scale mismatch is further amplified by the nonlinearity of harvest impacts. Retaining biodiversity requires non-uniform management, both at the stand and landscape level (Bunnell and Houde 2010). It also means that harvest impacts on biodiversity from the first harvest in a watershed are unlikely to be the same as those that occur after 50 percent of the area is harvested because the uniformity of the forested area will decrease up to a point and then it will increase.

Owing to the lack of a robust methodology to correctly assess harvest impacts on biodiversity and the lack of an impact category within TRACI to assess land use change factors that must be assessed at a landscape scale, such as biodiversity, it has not been assessed within this study.

Temporal aspects of the LCA also create challenges. Unlike carbon accounting analysis for agricultural crops, assessments of the carbon consequences of managing an average or representative forested hectare or yield with and without considering time are not analogous. Management on an average stand for a 50-year rotation can be used to represent the carbon impacts of forest operations per cubic meter of output if time dynamics are excluded as they are in this study. Because it takes 50 years to produce a harvestable stand with an average yield of 521 m^3/ha, the actual representative hectare in the wood basket from which the wood is removed in any given year is a conglomerate of 50 average stands capable of producing this average volume. Each of those stands is on a different year of their trajectory toward maturity. That representative hectare would include stands of ages 1 through 50 years. Data as presented herein are based on a cubic meter as functional unit. Were they to be scaled to a landscape level, they would first have to be converted to a per hectare basis and then allocated across the timescale.

Rather than relying on counterfactual assertions that begin after harvest but before site preparation and planting in order to assess the carbon consequences of harvest alternatives, it is relevant to examine what is occurring in the wood basket as a whole. In other words, whether the area and volume of forest is increasing, decreasing, or stable at the landscape level determines the ultimate carbon consequences of forest management activities. Figure 1 shows that harvest levels from private lands in Oregon have been essentially stable over the past 55 years, which is longer than a full rotation. This stable yield could arise from harvesting an equal volume per hectare per year, more area with less volume per hectare per year, or more volume over fewer hectares per year.

The conditions are less clear in Washington. Harvest levels from industrial and large private lands in Washington have declined over that 55-year period, most precipitously since the implementation of substantial regulatory changes in the late 1990s. The regulatory set-asides reduced the harvestable forestland base by 13.3 percent of the privately owned acres in western Washington (Perez-Garcia et al. 2012). Without extensive analysis, it is unclear if these regulatory changes are correlated with changes in overall harvest level or long-term carbon stability in the region. In short, without a full-scale timber supply analysis, there is no real way to discern whether overall carbon stocks are increasing or decreasing on a per hectare basis in either state that is part of the PNW region. What is known from broad-scale evaluations of forestland as represented in the US GHG inventories (EPA 2017) is that there has been approximately a 9.6 percent increase in forest-related carbon stocks from 1990 to 2016 with 8.5 percent of that increase found in the forest itself (EPA 2017, table 6-12). These increases in overall carbon stocks suggest that at an aggregated level, forest management activities are currently not depleting forest carbon stocks. A more geographically specific (but older) analysis for the PNW region indicates that forestland in the PNW coastal region continues to increase in total volume (Oswalt et al. 2014, US Forest Service 2016) though the contributions of private land to that increase are not disaggregated in that analysis.

Conclusions

This analysis expands and updates the PNW forest resources life-cycle inventory that was published by Johnson et al. (2005a, 2005b). The analysis includes elements that were not previously considered, including herbicide applications and fire hazard abatement. A comparison of the two data sets suggests that current management is perhaps a little more efficient than estimated by Johnson et al. (2005a), as reflected in its lower scores for GWP, smog, and eutrophication. Other impact factors were not comparable because the reference units have changed. Overall, these changes do not substantially alter the general idea that wood growth and harvest is a low carbon activity with many downstream benefits. The analysis has provided a significant update on common forest management activities as well as providing improvements in data completeness and quality that reflect a greater willingness among forest resource managers to share data in an effort to understand their environmental footprint and work to improve it.

While all LCA results are of interest for use in downstream applications, the carbon footprint of wood production is of significant interest because of the opportunity to use forests, wood products, and biofuels to address the challenges of climate change brought on by increasing CO_2 concentrations in the atmosphere. The LCIA indicates that under average management conditions, forest operations can expect to generate from 10.7 to 18.1 kg CO_2 eq per m^3 of log ready to leave the landing for the manufacturing facility, depending on the amount of forest residues that are piled and burned. This same cubic meter of log plus bark will have sequestered 960.4 kg CO_2 during its growth cycle. For every hectare of land managed for ongoing timber production in the PNW consistent with the management regime identified herein, there is 53 to 89 times more CO_2 eq sequestered than is emitted in the forest management and harvesting operations phase of production. Identifying economic and policy drivers that can support continued forest management that produces these positive environmental benefits would be a substantial contribution to the challenges of global climate change.

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