Cradle to Gate Life Cycle Assessment of US Regional Forest Resources – US Inland Northwest

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Abstract

The Inland Northwest softwood forests (hereafter INW forests) generate approximately 8% of US softwood products. In this region that encompasses Idaho, Montana, eastern Washington and eastern Oregon, nearly 60% of the harvested softwood volume comes from private lands, though there is an increasing amount from federal lands in recent measurement periods.

A combination of USFS Forest Inventory and Analysis (FIA) data and other secondary sources were aggregated and allocated to generate a life cycle impact assessment (LCIA) for the growth and harvesting of a cubic meter of INW softwood harvested logs (hereafter referred to as sawlogs). This system boundary was chosen to be consistent with the A1 module required by an Environmental Product Declaration for wood products. Overall, it takes 154 MJ of energy to produce a cubic meter of INW softwood sawlogs with a resultant Global Warming Potential (GWP) of thirteen kilograms of carbon dioxide equivalent per cubic meter (13.0 kg CO_2e/m^3) of sawlog harvested and loaded on the truck ready for transportation to the mill. This impact is approximately 1.6% of the CO_2e that is contained in a m^3 of INW softwood sawlogs. Substantial forest mortality from insects and disease is occurring across the region but it is not yet resulting in declining forest carbon stocks overall. However, there are sub-regions that show mortality plus harvest exceeding growth. If the mortality events increase to the extent that the entire regional wood supply region does not maintain stable or increasing carbon stocks, the LCA results will require adjustment to account for the overall carbon balance of the system. In a worst case scenario this is likely to increase the GWP from 13.0 kg CO_2e/m^3 of sawlog to 40.0 kg CO_2e/m^3 of sawlog harvested, or 5.5% of the CO_2e that is contained in a m^3 of INW sawlogs.

Keywords: *Inland Northwest softwood forestry, softwood LCA, life cycle assessment, environmental footprint, wood products, forest carbon, forest residue, fire risk reduction*

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Introduction

This study was designed to provide input data for estimating the environmental footprint of a cubic meter (m^3) of harvested softwood sawlogs from the Inland Northwest (INW) region of the US. The Inland Northwest is comprised of Idaho, Montana, Eastern Washington (EWA) and Eastern Oregon (EOR). Washington and Oregon are both separated into moist temperate rainforests to the west of the Cascade Mountain crest and dry interior forests to the east. These ecological differences lead to vastly different forest productivities, silvicultural requirements, and harvesting operations. For the most part the mountains effectively limit transport of logs between eastern and western Washington and Oregon rendering them effectively two regions. For these reasons, EWA and EOR are segregated from the westsides of these states and incorporated into the INW for analysis of the environmental impacts of forest operations where forest growth, yield, silviculture, and harvesting systems are similar.

This study synthesizes an array of data from secondary sources to generate estimates of the yield and emissions associated with softwood sawlog growth and harvest for this timber producing region. It updates the last lifecycle analysis of INW forests used for this purpose (Oneil et al. 2010), considers variability in production processes, and accounts for changes in life cycle reporting requirements.

Life cycle assessment (LCA) reporting requirements have changed to be consistent with the *North American Product Category Rules (PCR) for North American Structural and Architectural Wood Products Part B* (UL 2019) and *Part A: Life Cycle Assessment Calculations Rules and Report Requirements* (UL 2018) which dictate the requirements of wood product Environmental Product Declarations (EPD). As regional silvicultural and harvesting practices are key components of wood EPD, the data developed for this project are reported consistent with the requirements of the PCR and follow ISO 14040/44 (ISO 2006a-b) and ISO 21930 (ISO 2017) standards for conducting LCAs. Taken together these changes update and advance on the Oneil et al. (2010) reporting for INW softwood forests using current data and data allocation processes.

Forest Inventory and Analysis (FIA) data reported every decade by the United States Forest Service (Oswalt et al. 2019) is used to provide a general description of the timber resources, and to determine harvest allocations and product outputs from the region. These data are augmented by USFS PNW Research Station work products (Palmer et al., 2018, 2019), and University of Montana Bureau of Business and Economic Research (UM BBER, 2020) data on harvesting and milling operations across the region. After this overview, descriptions of LCA methods, limitations, and requirements are provided to establish the scale and scope of the regional analysis. Data development and analysis describe the literature sources and other background reference materials used to characterize the 'representative cubic meter' and its variability. Results are provided by cubic meter of sawlog, our functional unit for this analysis. Interpretation and discussion of the results are placed in the context of former studies and current opportunities to use these data to inform Environmental Product Declarations (EPD), and to support public policy debates regarding the carbon consequences of forest management operations.

Regional Description and Land Ownership Patterns

Timberland comprises approximately 77% of INW forests, with another 19% reserved from harvest and 5% unsuitable for harvesting operations due to low productivity (Table 1). The INW forests represent approximately 10.6% of US Timberland (Figure 1) (Derived from Oswalt et al. 2019, UM BBER 2020, Palmer et al., 2018, 2019).

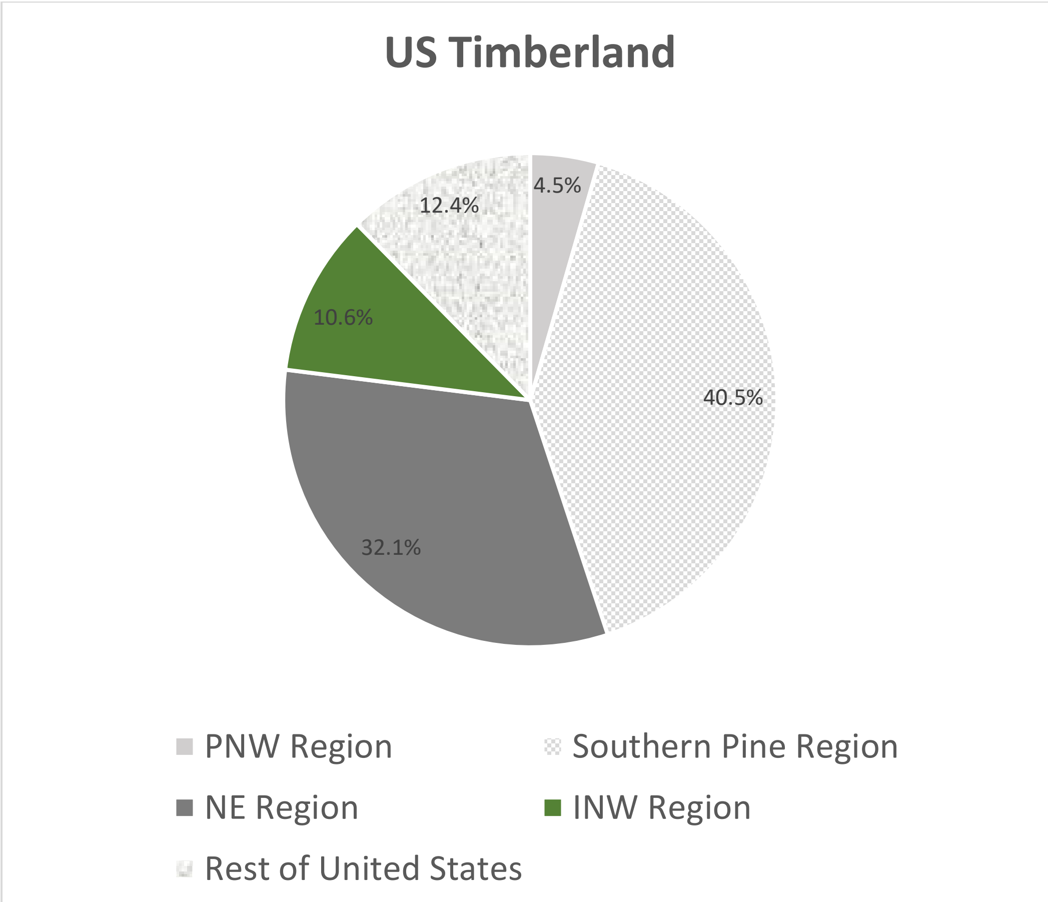

Figure 1: INW Region timberlands as a percent of US total timberlands

Table 1: Forest Area by state and sub-state, INW Region

Timberland, reserved and low productivity forest area (1000 acres)						
State and Sub-state	**Total forest**	**Timberland**	**Reserved Timberland**	**Reserved Other**	**Woodland**	**percent of INW Timberland**
EOR	14,435	10,268	1,383	153	2,632	19%
EWA	10,061	8,209	1,108	374	370	15%
Idaho	21,386	16,532	3,771	1,083	203	30%
Montana	25,517	19,768	3,768	1,980	367	36%
INW Region	71,399	54,777	10,030	3,589	3,572	100%

Inland Northwest softwood forests are experiencing massive mortality due to insects, disease, and wildfire (Table 2) (compiled from Oswalt et al. 2019, Palmer et al. 2018, 2019) which when coupled with harvests (removals) result in some states showing a decreasing inventory across their designated timberlands. Overall, the INW region still maintains an increasing inventory, but at a decreasing rate, as shown by the flat growing stock inventory line since the 1997 FIA reporting period (Figure 2) (Ibid).

Analysis of the eastern Washington and Oregon data indicate that most of the mortality is on public lands (81%) which represent 72% of total acres (Table 3), while 60% of the timber harvest comes from the 28% of timberland owned by private interests. Harvests from the INW represent approximately 8% of total US softwood harvests. Harvest volume is allocated to approximately 63% durable wood products (sawlogs, veneer logs, posts, poles and pilings) with the remainder to pulpwood, fuelwood, and other miscellaneous products (ibid).

Table 2 Inland Northwest Inventory Components of Change 2006-2015 (1,000 cubic feet/year)

State and/or Subregion	Net growth	Removals	Mortality	Net growth less removals
Idaho	441,238	230,262	616,491	210,976
EWA	91,867	167,394	479,429	(75,527)
EOR	341,155	146,370	267,672	194,785
Montana	54,778	102,171	662,369	(47,393)
Total	**929,038**	**646,197**	**2,025,961**	**282,841**

Table 3: INW timberland area by owner group (2017)

State	Year	All ownerships	Total public	Total Federal	State & local	total private
Idaho	2017	16,532	13,676	12,553	1,123	2,856
EWA	2017	10,061	6,028	5,028	1,000	4,034
EOR	2017	14,435	10,403	10,173	231	4,032
Montana	2017	19,768	13,919	12,988	931	5,849
Total		60,796	44,026	40,742	3,284	16,770

(Compiled from Oswalt et al. 2019, Palmer et al. 2018, 2019)

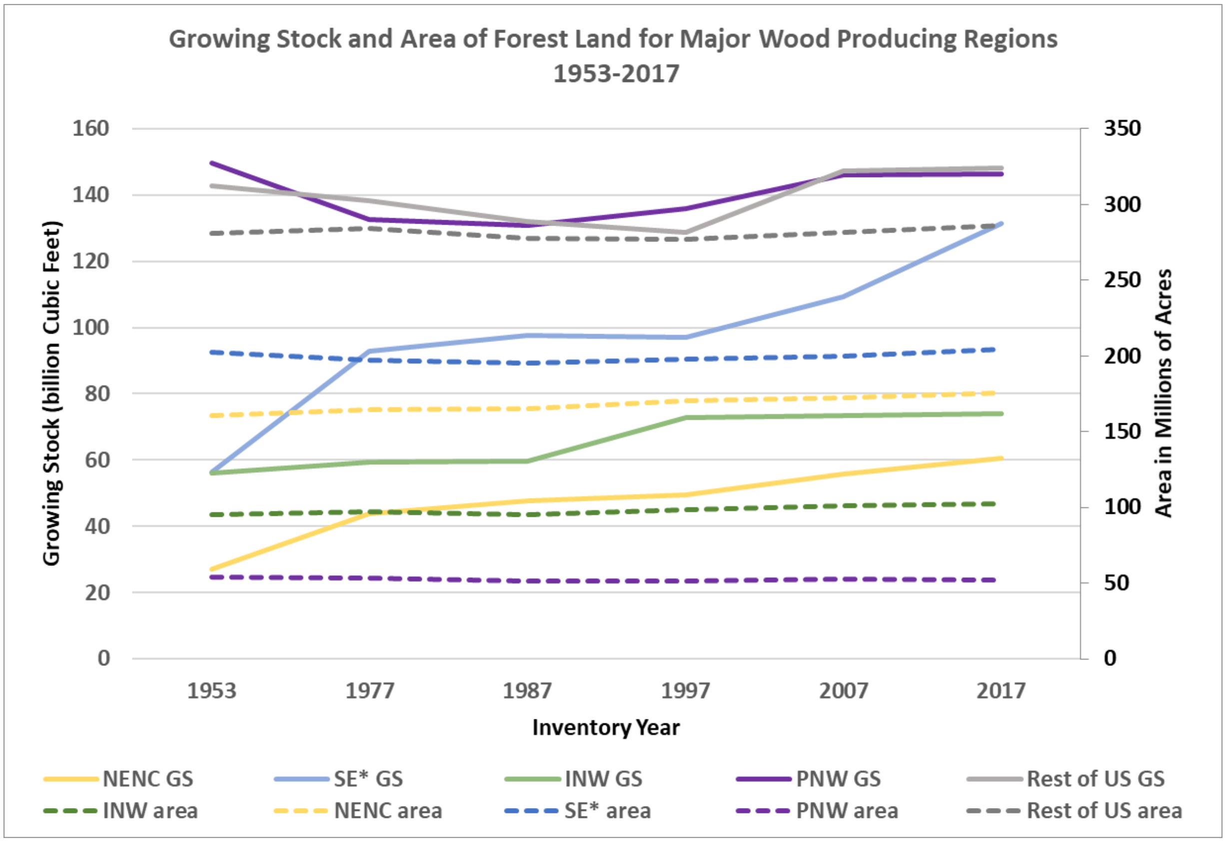

Figure 2 United States growing stock and timberland acreage 1953-2017. (Source data Oswalt et al. 2019)

Data on regional production and product types were used along with sub-regional data with greater specificity for allocations used to estimate the representative impact of producing softwood sawlogs from INW forests.

Methods

The International Organization for Standardization (ISO) defines LCA as an interconnected multiphase process consisting of four main elements: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (ISO 2016a, 2016b).

Life Cycle Assessment Goal and Scope Definition

The goal of this work is to update and revise energy and material inputs and outputs associated with the production of softwood sawlogs grown in the INW region of North America. The results can be used as upstream inputs for the development of LCA for all wood products that utilize sawlogs in their manufacturing process. Ultimately these LCA results will be used to quantify the environmental performance of durable wood products as part of regional, and/or national EPD development. The scope is limited to the evaluation of the inputs and outputs as defined by the system boundary (Figure 3). Evaluation of landscape level impacts of forest operations and the potential impacts to soil carbon and biodiversity are outside the scope of this analysis.

System Boundary

The system boundary (Figure 3) includes both silvicultural and harvesting operations. The INW region relies on a range of silvicultural inputs depending on management intensity. Treatments may include site preparation by piling debris or masticating residues or none at all. They may also include planting, fill planting or relying on natural regeneration after partial or clearcut harvests. Silvicultural inputs may include weed control for plantation establishment and thinning treatments to manage fire risk or may not occur at all. Thus, most inputs for silvicultural operations are (*) to indicate that they may or may not occur on a given forest stand (Figure 3). No onsite fertilization is reported for INW softwood production beyond the amounts used to grow seedlings.

The system boundary also includes harvesting operations that generate sawlog quality material. Harvesting operations 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 ready for shipment. Hauling is not reported in this analysis as distances and equipment types are specific to wood processing facilities and reported in mill surveys. Inputs include seedlings, fuel, fertilizer, and electricity to grow seedlings, fuel and herbicides used for site preparation and weed control, fuels, lubricants, and oils used for stand management and harvesting activities including transport of crew and materials. Outputs include emissions related to the production of 1 cubic meter (m^3) of logs destined for a wood product manufacturing facility, co-products, and waste including forest residues.

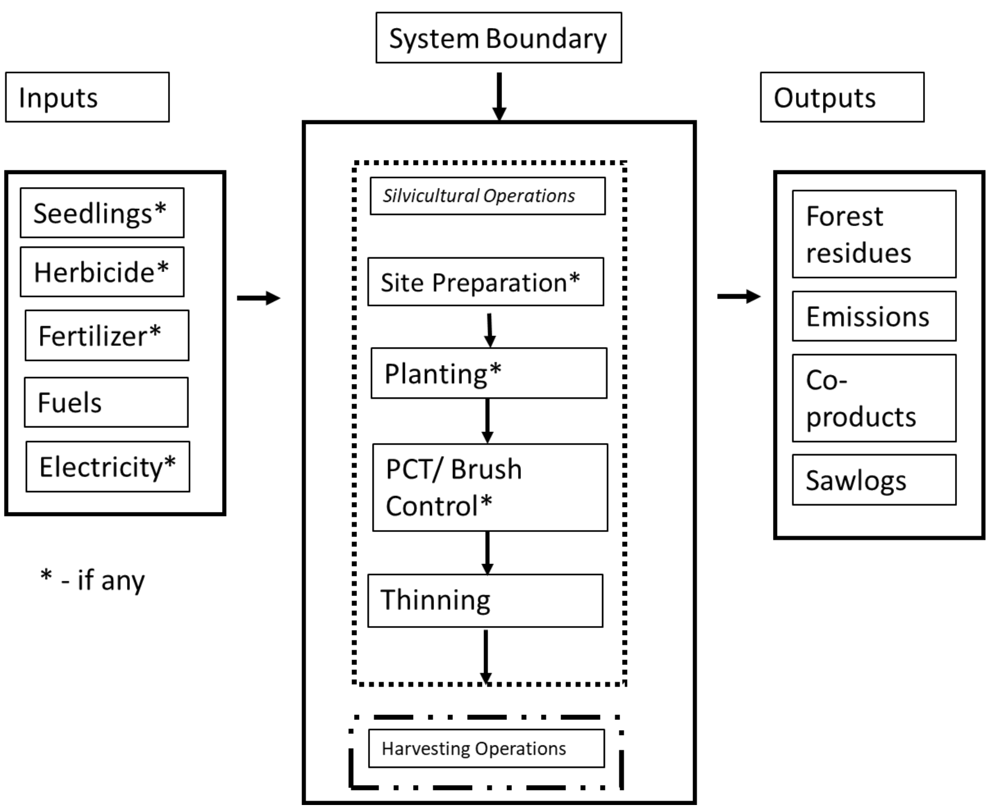

Figure 3: System boundary for the Inland Northwest forest resources LCA

Functional Unit

The results are based on 1 m^3 of logs delivered to the manufacturing facility. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with International Organization for Standardization (ISO) protocols (ISO 2006). The allocation is based on oven-dry weight of the logs.

When trees are harvested, the tops, limbs, damaged boles, and undersized trees are left behind as forest residues. These residues either decay in situ or can be 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 fiber, it becomes a co-product and can be assigned upstream forestry burdens and consequent impacts. Burdens associated with these non-sawlog uses were allocated to the non-sawlog and leave the system boundary. If the material is left to decay in-situ it leaves the system boundary as a forest residue. If the material is burned to meet fire hazard abatement regulations, or to increase plantable spots, it generates emissions that are captured in the life cycle and allocated to the harvested wood volume. In the INW region, burning forest residues is a common practice as it serves a dual role of reducing fire risk. Therefore, burning residues is included as part of this analysis and is also dealt with in detail in the variability analysis.

Life Cycle Inventory

The key component in an LCA is the life cycle inventory (LCI). The LCI is an objective, data-based process of quantifying energy and raw material inputs, air emissions, waterborne effluents, solid waste, and other environmental releases occurring within the system boundary. These data are the quantitative inputs used to develop the life cycle impact assessment (LCIA).

Life Cycle Impact Assessment

The LCIA phase establishes links between the LCI results and potential environmental impacts. The LCIA calculates impact indicators for specific emission types (Table 4). These impact indicators provide general, but quantifiable, indications of potential environmental impacts. Environmental impacts are determined using the TRACI method (Bare 2011) for this LCIA. Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators. Additionally, each impact indicator value is stated in units that are not comparable to each other. Thus, indicators should not be combined or added. The LCIA results are relative expressions and therefore do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Table 4 Selected impact category indicators reported in this study

Impact category	Unit	Impact Method
Ozone depletion	kg CFC-11 eq	TRACI 2.1 V1.05
Global warming	kg CO2 eq	TRACI 2.1 V1.05
Smog	kg O3 eq	TRACI 2.1 V1.05
Acidification	kg SO2 eq	TRACI 2.1 V1.05
Eutrophication	kg N eq	TRACI 2.1 V1.05
Carcinogenics	CTUh	TRACI 2.1 V1.05
Non-carcinogenics	CTUh	TRACI 2.1 V1.05
Respiratory effects	kg PM2.5 eq	TRACI 2.1 V1.05
Ecotoxicity	CTUe	TRACI 2.1 V1.05
Fossil fuel depletion	MJ surplus	TRACI 2.1 V1.05

Energy use is based on lower heating values using the Cumulative Energy Demand (CED) calculated from data published by Ecoinvent and expanded by PRé (2020) for energy resources available in the SimaPro database (v. 9.1.1.1). Characterization factors are given for six impact categories: 1.) Non-renewable, fossil, 2.) Non-renewable, nuclear, 3.) Non-renewable, biomass, 4.) Renewable, biomass, 5.) Renewable, wind, solar, geothermal, and 6.) Renewable, water.

Interpretation

As defined by ISO (2006), the term life cycle interpretation is the phase of the LCA where the findings of either the LCI or the LCIA, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations. This phase in the LCA reports the significant issues based on the results presented in the LCI and LCIA. Additional components evaluate completeness, conduct sensitivity analysis, and check consistency of the LCI and LCIA results, relative to the conclusions, limitations, and recommendations.

LCA results in this study are presented that meet the requirements for Environmental Product Declaration (EPD) information module A1 – resource extraction of raw materials and processing for INW softwood forestry operations only. No downstream use or treatment is included in this analysis, though it can be expected to be used by downstream processes such as lumber manufacture and whole building LCA. Secondary data sources, including literature sources and prior datasets were combined to develop this cradle-to-gate LCA of forestry operations for harvested logs coming from INW timberland for the production of wood products. Results are not suitable for assessing the LCA of small diameter timber harvests that are sometimes used to mitigate fire risk or to complete forest restoration goals in these dry, fire dependent forested systems.

Data Development

Allocation

No primary data using time-motion studies or similar methods were collected for this project. Forest growth and yield from the USFS FIA reports (Oswalt et al. 2019, Palmer et al. 2018, 2019) were combined with survey data on harvested wood volume (UM BBER 2020, Berg et al. 2018) to generate allocations for harvest volume by location (state or half-state) and by owner type (federal, state, and private).

Approximately 47% of the INW harvest comes from Idaho, 15% from Montana, 22% from Eastern Washington (EWA), and 16% from Eastern Oregon (EOR) (Table 5). Most harvest volume is removed from private and tribal forestry operations (60%), with the remainder from public lands. Variability in land ownership patterns between the states (Table 3) explains some, but not all, the variability in ownership contributions to total harvest volume between the subregions.

Harvest data were combined with data from Simmons et al. 2013 to develop an allocation of delivered logs by diameter distribution that was used to generate the allocations for softwood harvest volume by piece size removed for the INW region (Table 6). The area and volume allocations were used to estimate the relative percentage of different silvicultural and harvesting operations that are incorporated into the LCIA results.

*Table 5: INW Harvest Statistics and State Allocations 2011-2018**

Inland NW average harvest volume (MBF) by owner type and state: 2011-2018						
State	**Private & Tribal**	**State**	**US Forest Service**	**Other Public**	**Total Harvest Volume**	**Cumulative Value**
Idaho	653,809	285,253	158,286	6,809	1,104,156	1,104,156
EWA	367,513	66,257	76,844	4,859	515,474	1,619,630
EOR	234,021	13,890	121,224	9,807	378,942	1,998,572
Montana	163,764	53,944	134,965	7,284	359,956	2,358,529
Total	1,419,107	419,344	491,319	28,759	2,358,529	
Harvest Volume by owner as a percent of state and regional harvest						
Idaho	59%	26%	14%	1%	100%	-
EWA	71%	13%	15%	1%	100%	-
EOR	62%	4%	32%	3%	100%	-
Montana	45%	15%	37%	2%	100%	-
Total	60%	18%	21%	1%	100%	-
State harvest as a percent of total harvest volume						
Idaho	46%	68%	32%	24%	47%	47%
EWA	26%	16%	16%	17%	22%	69%
EOR	16%	3%	25%	34%	16%	85%
Montana	12%	13%	27%	25%	15%	100%
Total	100%	100%	100%	100%	100%	

* collated from UM BBER (2020) harvest by county data. EWA = Eastern Washington, EOR = Eastern Oregon.

Table 6 Allocation of softwood harvest volume by piece size and volume removed

Diameter class	Percent harvested trees	Percent harvested volume	Forest Residues (m^3/m^3 sawlogs)
6	6.5%	1.1%	0.197
8	18.2%	5.4%	0.154
10	19.1%	9.8%	0.139
12	17.8%	13.7%	0.136
14	12.4%	13.6%	0.132
16	9.8%	14.5%	0.137
18	6.3%	12.7%	0.132
20	4.4%	10.6%	0.128
22	2.1%	5.7%	0.124
24	2.0%	7.4%	0.118
26	0.8%	3.5%	0.154
28	0.4%	1.3%	0.140
30	0.4%	0.6%	0.103
Total (weighted)	100.0%	100.0%	0.134

Silvicultural Operations Scenarios

An INW seedling survey (Nelson 2021) estimates that 19,087,527 seedlings were planted across the region in 2019, with approximately 35% of the respondents indicating that they either planted 100% of the time or used a mix of planting and natural regeneration. There is some uncertainty in the estimate of acres planted as the ratio is based on respondent count and not respondent acres. The ratio of seedlings planted to prior year's harvest volume (as trees are planted after harvest) was used to generate an estimate of 8.09 trees planted per MBF of harvested timber. Planting is assumed to occur on 35% of the area, with LCI inputs developed for growing the seedlings, and seedling and planter transport based on survey data for transportation distances (Puettmann et al. 2010) and prior greenhouse survey data (Oneil et al. 2010).

Site preparation in the form of chemical application of forestry herbicides is not that common in the region. It was assumed to occur once on 60% of acres under industrial management with inputs adapted from Oneil and Puettmann (2017). We assumed that landing piles were burned to reduce fire risk and create access and plantable spots, but in-woods material was left to decay in-situ and left the system boundary. No additional piling after harvest operations was modeled. Using these assumptions, site preparation in the form of pile burning occurs 81% of the time, consistent with the estimated percentage of harvest volume that is merchandized at the landing (Simmons et al. 2013).

The amount of forest residues produced and consumed was based on growing stock (greater than 5" diameter) residue estimates from Berg et al. (2016) combined with foliage and top residue estimates by diameter class using Jenkins et al. (2004) biomass equations. The total residue ratio was allocated based on harvest volume by diameter class to generate a weighted average residue ratio, and percent coarse and fine fuels for harvests in the INW. Emissions from pile burning were based on relationships for burning residues found in Battye and Battye (2002) and Prichard et al. (2006).

Table 7: Forest Residue Burning Inputs.

growing stock residues per 1000 m^3	growing stock residue/m^3	Residue Ratio (coarse plus fine)	percent fine fuels	percent coarse fuels
31.99	0.032	0.134	76%	24%

Harvest Operations

The allocation among equipment systems was based on survey data from Simmons et al. (2013) (Table 8). Data on equipment productivity, fuels and ancillary materials, and transportation of crew and equipment harvesting operations were developed from the spreadsheet models for Oneil et al. (2010) that were updated to include estimates of equipment efficiency by logging system (Han et al. 2017, Hayes and Niccolucci, 2020) and expanded to include more upstream inputs for equipment operation. These data were used as inputs to the SimaPro (Pre 2020) software to generate a LCIA and LCA consistent with North American Wood Product Category Rule requirements. Variability around these input parameters were used to create estimates of uncertainty for harvesting operations.

Table 8: Harvest equipment use and utilization.

Harvest Activity	Method	Percnet Activity type
Felling equipment	chainsaw	35%
	mechanical	58%
	mixed	7%
Yarding system	ground	86%
	cable	14%
Skidding	tree length	83%
	log length	17%
Merchandizing location	in unit	13%
	at landing	87%
Merchandizing method	hand	19%
	mechanical	81%
loading		1005

As the representative stand and harvest conditions developed as inputs to the LCIA are an amalgamation of many different treatment alternatives and stand conditions, the LCIA results are applicable as inputs for large scale analyses such as inputs for a INW lumber production LCA. This representative stand condition does not reflect a specific location or stand condition, and as such it should not be used for small scale analysis without adaptation to include specific local input parameters.

Results and Discussion

Life Cycle Impact Assessment

The data generated from published surveys and large scale datasets demonstrate wide variability in productivity and management inputs across the INW region. This variability is distilled into a "representative" m^3 of sawlogs needed as an output from the forest resources module (A1) for downstream uses in EPD. Based on allocations derived from Table 5 through Table 8, the representative LCIA results per m^3 of INW sawlogs are found in Table 9 (absolute basis) and in Table 10 (relative basis). Silvicultural operations emissions include non-CO_2e emissions from burning forest residues at the landings post-harvest, but do not include direct CO_2 emissions from biomass burning consistent with the TRACI impact assessment methodology (Bare 2011).

Eighty two percent (82%) of the GWP of a representative m^3 of sawlog is attributable to harvesting operations (Table 10). Silvicultural operations are responsible for 69% of ozone depleting emissions, 65% of carcinogenic emissions, and 99% of emissions with potential respiratory impacts (Table 10). Except for ozone depletion most of the emissions related to silvicultural operations are attributable to residue burning (Table 13, Table 14).

Table 9 LCIA result summary for one cubic meter of INW softwood sawlog for silvicultural operations and harvesting operations. (Absolute values)

Impact category	Unit	Silvicultural operations	Harvest operations	Total
		per m^3 of sawlog		
Ozone depletion	kg CFC-11 eq	1.88E-08	8.57E-09	2.74E-08
Global warming	kg CO2 eq	2.39E+00	1.07E+01	1.30E+01
Smog	kg O3 eq	3.46E+00	4.50E+00	7.96E+00
Acidification	kg SO2 eq	1.36E-01	1.42E-01	2.78E-01
Eutrophication	kg N eq	6.71E-03	8.93E-03	1.56E-02
Carcinogenics	CTUh	3.11E-07	1.65E-07	4.76E-07
Non carcinogenics	CTUh	2.57E-08	1.59E-06	1.62E-06
Respiratory effects	kg PM2.5 eq	2.11E-01	2.83E-03	2.14E-01
Ecotoxicity	CTUe	1.35E+00	3.28E+01	3.41E+01
Fossil fuel depletion	MJ surplus	3.00E-01	2.25E+01	2.28E+01

Table 10 LCIA result summary for one cubic meter of INW softwood for silvicultural operations and harvesting operations. (Relative values)

Impact category	Unit	Silvicultural operations	Harvest operations	Total
			per m^3 of sawlog	
Ozone depletion	kg CFC-11 eq	68.7%	31.3%	100%
Global warming	kg CO2 eq	18.3%	81.7%	100%
Smog	kg O3 eq	43.4%	56.6%	100%
Acidification	kg SO2 eq	49.0%	51.0%	100%
Eutrophication	kg N eq	42.9%	57.1%	100%
Carcinogenics	CTUh	65.3%	34.7%	100%
Non carcinogenics	CTUh	1.6%	98.4%	100%
Respiratory effects	kg PM2.5 eq	98.7%	1.3%	100%
Ecotoxicity	CTUe	4.0%	96.0%	100%
Fossil fuel depletion	MJ surplus	1.3%	98.7%	100%

The cumulative energy demand for the representative m^3 of sawlogs is shown in Table 11 on an absolute basis and in Table 12 on a percentage basis. Energy use was dominated by non-renewable fuels used during final harvest of the merchantable sawlog (98.2%) (Tables 11 and 12). On average, it takes 154 MJ of energy (Table 11) to produce a representative m^3 of INW sawlogs loaded at the landing and ready for transportation to the manufacturing facility. To produce those sawlogs 13.0 kg CO_2e are emitted, along with other chemical equivalents as shown in Table 9. These results reflect the inputs and emissions to produce all commercially recoverable logs (sawlog, hewsaw, and pulp). While silvicultural operations are responsible for a higher percentage of some energy types (Table 12), overall silvicultural operations represent only 1.8% of total energy demand.

Table 11 Cumulative Energy Demand for one cubic meter of INW softwood sawlog for silvicultural operations and harvesting operations. (Absolute basis)

Impact Category	Unit	Silvicultural operations	Harvest operations	Total
		per m^3 of sawlog		
Non renewable, fossil	MJ	2.56E+00	1.51E+02	1.53E+02
Non-renewable, nuclear	MJ	1.28E-01	4.05E-01	5.33E-01
Non-renewable, biomass	MJ	4.27E-07	1.05E-07	5.32E-07
Renewable, biomass	MJ	1.71E-02	1.02E-02	2.74E-02
Renewable, wind, solar, geothermal	MJ	2.49E-04	1.40E-02	1.42E-02
Renewable, water	MJ	7.72E-04	3.58E-02	3.66E-02
Total	MJ	2.70E+00	1.51E+02	1.54E+02

Table 12 Cumulative Energy Demand for one cubic meter of INW softwood sawlog for silvicultural operations and harvesting operations. (Relative basis)

Impact Category	Unit	Silvicultural operations	Harvest operations	Total
		per m^3 of sawlog		
Non-renewable, fossil	MJ	1.7%	98.3%	100%
Non-renewable, nuclear	MJ	24.1%	75.9%	100%
Non-renewable, biomass	MJ	80.3%	19.7%	100%
Renewable, biomass	MJ	62.5%	37.5%	100%
Renewable, wind, solar, geothermal	MJ	1.8%	98.2%	100%
Renewable, water	MJ	2.1%	97.9%	100%
Total	MJ	1.8%	98.2%	100%

Table 13 LCIA result summary for partitioned silvicultural operations for one cubic meter of INW softwood sawlogs. (Absolute values)

Impact category	Unit	Other silvicultural operations	Residue Burning	Total
		per m^3 of sawlog		
Ozone depletion	kg CFC-11 eq	1.88E-08	0.00E+00	1.88E-08
Global warming	kg CO2 eq	1.57E-01	2.23E+00	2.39E+00
Smog	kg O3 eq	2.33E-02	3.43E+00	3.46E+00
Acidification	kg SO2 eq	1.31E-03	1.35E-01	1.36E-01
Eutrophication	kg N eq	5.17E-04	6.19E-03	6.71E-03
Carcinogenics	CTUh	2.96E-09	3.08E-07	3.11E-07
Non carcinogenics	CTUh	2.17E-08	4.08E-09	2.57E-08
Respiratory effects	kg PM2.5 eq	8.16E-05	2.11E-01	2.11E-01
Ecotoxicity	CTUe	7.33E-01	6.19E-01	1.35E+00
Fossil fuel depletion	MJ surplus	3.00E-01	0.00E+00	3.00E-01

Table 14: LCIA result summary for partitioned silvicultural operations for one cubic meter of INW softwood sawlogs. (Relative values)

Impact category	Unit	Other silvicultural operations	Residue Burning	Total
			per m^3 of sawlog	
Ozone depletion	kg CFC-11 eq	100.0%	0.0%	100%
Global warming	kg CO2 eq	6.6%	93.4%	100%
Smog	kg O3 eq	0.7%	99.3%	100%
Acidification	kg SO2 eq	1.0%	99.0%	100%
Eutrophication	kg N eq	7.7%	92.3%	100%
Carcinogenics	CTUh	1.0%	99.0%	100%
Non carcinogenics	CTUh	84.2%	15.8%	100%
Respiratory effects	kg PM2.5 eq	0.0%	100.0%	100%
Ecotoxicity	CTUe	54.2%	45.8%	100%
Fossil fuel depletion	MJ surplus	100.0%	0.0%	100%

Variability and Uncertainty

Uncertainty and representativeness analyses are required under the North American PCR (UL 2019) for all modules of an EPD. For the INW analysis, the impacts of harvest system type and average diameter were used as a proxy for differences in management outcomes with specific emphasis on utilization parameters that influence residue volume remaining on site and its potential emissions from open burning. Utilization and recovery data derived from Simmons et al. (2013) and Berg et al. (2016), harvest allocation data from UM BBER (2020), and biomass correlations from Jenkins et al. (2004) were used to estimate the range of total residues likely to remain on site after all merchantable wood is removed. As fire risk mitigation activities are commonly employed across the region, usually through pile burning or broadcast burning to reduce combustible material, the residue ratios inform estimates of emission potential from these activities.

LCA impacts from fire risk reduction activities are reported for the weighted average scenario for the INW in Table 9 through Table 14, but for this examination of variability and uncertainty we focus on variability in residue ratios as an input parameter used to estimate open burning impacts. A residue ratio is the ratio of unharvested material remaining onsite after harvest, relative to the amount of material removed during the harvest. Residue ratios of the growing stock bole component remaining onsite are assessed to support the FIA reporting on harvested wood products and growing stock changes (Berg et al. 2016). The growing stock bole component is that part of the tree bole that is greater than 5 inches DBH and at least 4 inches at the top diameter for INW softwood forests. These data were combined with estimates of non-growing stock components, including tops of the bole less than 4” diameter, branches, and stumps remaining onsite using Jenkins et al. (2004) component ratio methods. Together these data sources were used to calculate the total residues remaining onsite for a range of harvest systems reported by Berg et al. (2016) and calculated for a weighted average harvest scenario for the INW. Additional granularity was included to assess the variability in residue ratios across a range of diameter classes (Figure 4), including an examination of the impacts on residue ratios from small diameter harvests (Figure 5), here represented as removals of material averaging 6” dbh.

As reported in Berg et al. (2016), the largest variability in residue ratios is driven by whether a pulp market exists to utilize small diameter material (Figure 4). Where it cannot be removed due to lack of markets or insufficient price, residue ratios increase by 28-30% for a given harvest type. Assuming a similar percentage of material is burned to reduce fire risk across market conditions, a lack of pulp markets translates into a 28-30% increase in emissions from pile burning for site preparation and fire risk reduction. For a given level of pulp recovery, differences in residue ratios between merchantable diameter classes is less significant than harvest type (mechanized, hand falling, or a combination) (Figure 4).

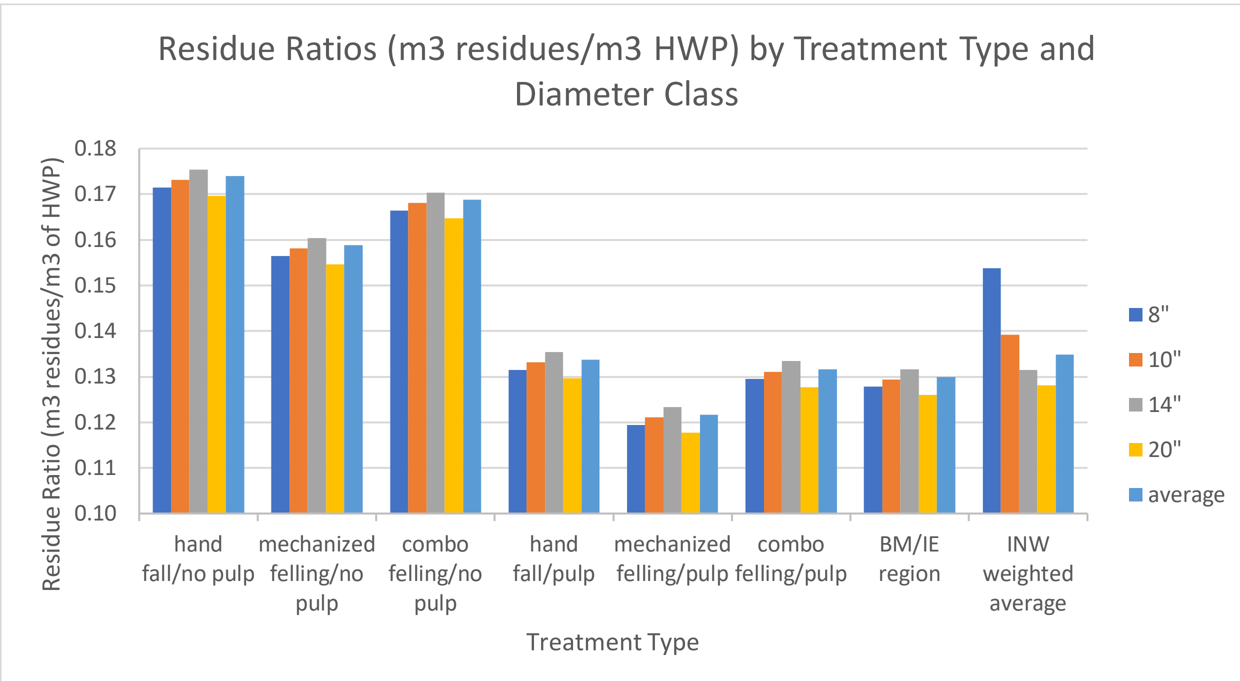

Figure 4: Cubic meters of residue per m^3 of harvested wood product for select harvest systems in the INW

The impact of no pulp market is further amplified when trying to remove small diameter material. Comparisons show that residue ratios for small diameter harvests increase 45% relative to the INW weighted harvest data and 25-35% by broad harvest type (Figure 5). This result is consistent with expectations as small diameter trees have relatively more tops/limbs to bole volume than larger diameter trees that make up the bulk of current regional harvests.

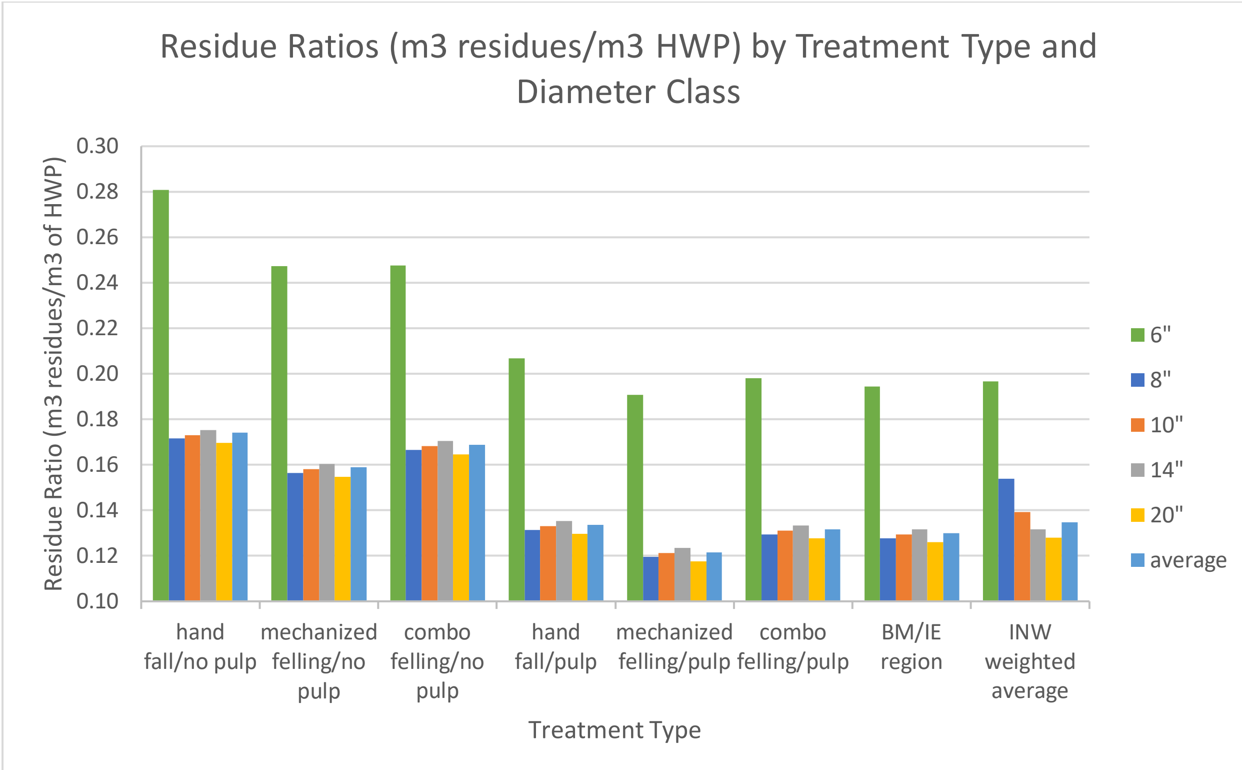

Figure 5: Cubic meters of residue per m^3 of harvested wood products – small diameter harvests

As harvest operations dominate the LCIA for most indicators, a closer examination of the variability in harvest system efficiencies was also conducted. Table 15 provides a 95% confidence interval for in GWP (kg CO_2e per m^3) and Cumulative Energy Demand (MJ) that captures the variability in harvest system alternatives modeled for the INW. This uncertainty estimate incorporates differences in productivity between harvest systems used for clearcutting and three levels of partial harvest removal (4, 7 and 10 MBF/acre respectively). Uncertainty estimates do not include allocation and therefore the average is not the same as the harvesting impacts reported in Table 9.

Table 15: Variability in Harvest Operations

Impact Category	Unit	Lower CI	Average	Upper CI
		per m^3 sawlog for harvest system operations		
Global warming Potential	kg CO_2 eq	9.0	10.6	12.2
		per m^3 sawlog for harvest system operations		
Cumulative Energy Demand (LHV)	MJ	129	151	172

Biogenic Carbon

A m^3 of bone dry logs from the INW is estimated to contain 225 kg carbon or 825 kg CO_2e (Puettmann, 2019). On average, the 2.39 kg CO_2e/m^3 that is generated from silvicultural operations represent 1.8% of fuel use (Table 12) but 18.3% of the GWP of sawlog production (Table 10). The large differences in fuel use and GWP percentages are driven by the reportable non-CO_2e emissions from open burning (e.g., methane, nitrous oxides, etc) which account for 93% of GWP impacts for silvicultural operations (Table 14). As the PCR requires reporting consistent with the TRACI method (Bare 2011), the carbon dioxide (CO_2) emissions from burning forest residues are not reported as they are biogenic in origin. Using the TRACI method, the total GWP/m^3 for silvicultural and harvesting operations is estimated at 13.0 kg CO_2e. The GWP for producing INW sawlogs translates to a ratio of emissions from silvicultural and harvesting operations (EPD Module A1) to sequestered CO_2e in the sawlog of 1.6%. These values are calculated using the formula:

GWP per m^3 /kg CO_2e stored per m^3 x 100 (to express the ratio as a percent).

This weighted average GWP is representative of current volume and piece size recovery where an estimated 1% of logs are 6" diameter. Changes to operational conditions that result in a larger percentage of small diameter timber removed and processed into usable products will increase the GWP for both silvicultural and harvesting operations. The increase in silvicultural operations will be driven by increases in the amount of forest residue (Figure 5), whereas increases in harvesting operations will be driven by decreases in harvest system efficiency and recovery that arise when handling small diameter material. For these reasons, this biogenic carbon analysis is not well suited for application to the harvest of small diameter timber harvest as it would under-estimate the GWP for producing the sawlogs and therefore under-estimate the relative percent impacts per m^3 of harvested wood.

Analysis was also completed to compare the carbon dynamics of including biogenic CO_2 emissions from residue burning in the GWP calculations. To maintain the LCIA mass balance, the material that is consumed as part of forest residue combustion is included in the kg CO_2e stored per m^3 calculation using the following formula:

(GWP per m^3 (TRACI) + GWP (biogenic CO_2 emissions)/ (kg CO_2e sequestered per $m^3$of forest residues + kg CO_2e stored per m^3) x 100 (to express the ratio as a percent).

Using this equation, the carbon balance of the system becomes (2.38 + 37.66)/(91.78 + 825)*100, which translates to a ratio of emissions from silvicultural and harvesting operations (EPD Module A1) to sequestered CO_2e in the sawlog of 5.5%. Allocating the carbon balance between these methods would need to be adopted if the ISO 21930 requirement for stable or increasing carbon stocks on the landscape were not met. Currently the FIA data (Oswalt et al. 2019, Palmer et al., 2018, 2019) indicate that the INW continues to maintain increasing carbon stocks despite the substantial mortality from insects and disease that is concentrated on public lands, though sub-regions of the INW are showing declines in forest carbon stability.

Differences from Prior INW Region Study

Oneil et al. (2010) did not provide LCIA using the TRACI method that is required for wood product EPD published under current criteria (UL 2018, 2019). Instead, they reported results as a dimensionless metric, the Eco-indicator 99 (E) / Europe EI 99 E/E. In 2017, the underlying data used in Oneil et al. (2010) were updated to include the newer North American grid and a new LCIA was generated using the North American TRACI method for use in the updated North American wood product EPD (CORRIM unpublished data). These data were compared to the current analysis (Table 16). In Oneil et al. (2010), the LCIA modeled three general cases for softwood forest management: state and private dry forests, state and private moist forests, and USFS forests. The current analysis relied on forest growth and yield from the USFS FIA reports (Oswalt et al. 2019, Palmer et al. 2018, 2019), survey data on harvested wood volume (UM BBER 2020, Berg et al. 2018), piece size (Simmons et al. 2013, 2017), and recovery (Berg et al. 2016). Percentage differences by impact category shown in Table 16 vary from -114 to 28% though absolute differences are small (less than 1 unit for most impact categories/m^3 of roundwood). For comparison purposes, data in Table 16 are reported for roundwood (i.e., include the pulp and other product portion of harvested wood volume).

These differences in the LCIA between the 2010 analysis and this report reflect the additions of inputs related to the combustion of forest residues, higher quality data on estimating residue amounts, location, and combustion, access to higher quality data on equipment usage, and greater detail on upstream processes that contribute to overall environmental footprint.

Table 16 Comparison of previous LCA study by Oneil et al. (2010) and this report (2021) for A1 system boundary.

Impact category	Unit	2010 updated for 2017 AWC EPDs	Current report (2021)	Difference, percent change from 2005 to 2021
		Per cubic meter of roundwood at road		
Ozone depletion	kg CFC-11 eq	5.84E-08	2.74E-08	-114%
Global warming	kg CO2 eq	1.05E+01	1.30E+01	20%
Smog	kg O3 eq	5.80E+00	7.96E+00	27%
Acidification	kg SO2 eq	2.00E-01	2.78E-01	28%
Eutrophication	kg N eq	1.34E-02	1.56E-02	14%
Carcinogenics	CTUh	3.85E-07	4.76E-07	19%
Non carcinogenics	CTUh	1.54E-06	1.62E-06	5%
Respiratory effects	kg PM2.5 eq	1.57E-01	2.14E-01	27%
Ecotoxicity	CTUe	4.10E+01	3.41E+01	-20%
Fossil fuel depletion	MJ surplus	1.90E+01	2.28E+01	17%

Data Quality

Data quality parameters relevant to the LCIA are summarized in Table 17. These parameters include data source, geography, and age.

Table 17: Data Quality for Raw Material Inputs

A1: Raw Material Inputs				
Inputs	**LCI Data Source**	**Geography**	**Year**	**Data Quality Assessment**
Seedlings, Herbicides, Adjuvants, Fuels, Lubricants	Database: CORRIM dataset US EI 2.2 (DataSmart2018) Process: Silvicultural Operations	North America	2021	**Technology**: good Process models represent weighted average operations. **Time**: good: Data is less than 10 years old **Geography**: good
Fuels, Lubricants, Coolants	Database: CORRIM dataset US EI 2.2 (DataSmart2018) Process: Harvesting Operations	North America	2012 - 2019	**Technology**: good Process models average US technology **Time**: good: Data is less than 10 years old **Geography**: good Data is representative of INW regional operations

Conclusions

Most of the LCA impacts for INW softwood sawlog production comes from harvest operations. Equipment systems, and their efficiency, are driven by harvest intensity (percent removal), markets, topography, and ownership. Detailed data on equipment system allocation has improved the certainty of the estimates for this LCIA over prior studies.

There is a significant LCIA impact from burning forest residues in the INW. Depending on the LCIA method used, the CO_2e emissions for producing 1 m^3 of INW softwood sawlogs varies from 1.6-5.5% of the amount of CO_2e stored in that sawlog. Differences are driven by the inclusion (or exclusion) of carbon dioxide equivalents from burning forest residues to address post-harvest fire risk. Treatment of biogenic carbon in LCIA is a function of the condition of the forest inventory. If the inventory is stable or increasing as it is in the INW, then burning forest residues does not count towards the CO_2e impact as the land use change account has already captured that change. In this case the GWP for 1 m^3 of INW sawlogs represents 1.6% of the CO_2e stored in that same 1 m^3 of wood.

The representative impacts for producing INW sawlogs generated here, including uncertainty, can be used as the upstream input for future life cycle assessments of INW products including lumber, plywood, and engineered wood products. It's utility for small diameter timber harvests or forest restoration activities is severely limited without modifying the harvesting input data, allocation methods, and residue assumptions to accurately reflect the differences in expected impact. This need is particularly germane for harvests where the mean diameter removed is less than 10 inches.

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Appendix I – Regional harvest by year and ownership

Table 18: INW regional harvest by year and owner type group 2002-2018 (in MBF)

Year	Private & Tribal	State	US Forest Service	Other Public	Total Harvest Volume/year
2002	2,518,833	302,557	477,606	22,499	3,321,495
2003	2,004,339	307,595	458,610	19,297	2,789,839
2004	2,101,215	438,385	571,057	21,754	3,132,411
2005	2,065,940	330,941	511,571	22,531	2,930,981
2006	2,034,898	319,011	279,929	28,055	2,661,892
2007	1,790,087	339,812	409,781	19,097	2,558,776
2008	1,432,990	341,704	457,956	25,234	2,257,884
2009	1,002,933	301,597	416,914	22,490	1,743,933
2010	1,212,761	413,764	430,830	27,637	2,084,991
2011	1,299,849	470,409	497,931	36,015	2,304,204
2012	1,295,430	428,352	403,025	26,752	2,153,558
2013	1,568,138	533,880	423,884	21,550	2,547,453
2014	1,522,922	397,871	467,386	21,812	2,409,992
2015	1,652,415	407,705	469,187	32,951	2,562,258
2016	1,411,376	370,910	494,581	18,115	2,294,981
2017	1,281,220	348,633	577,939	23,279	2,231,071
2018	1,496,574	396,995	596,618	49,597	2,539,784
Grand Total	27,691,920	6,450,121	7,944,805	438,665	42,525,503