Cradle to Gate Life Cycle Assessment of US Regional Forest Resources – US Northeast/North central

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Abstract

The Northeast (NE) and Northcentral (NC) softwood forests (hereafter NENC forests) generate approximately 7% of the US softwood products, and nearly 60% of U.S. hardwood forest products from 32.1% of US timberlands. Nearly 80% of the harvested softwood volume comes from private lands, and 75% of it comes from just four states: Maine, Michigan, Wisconsin, and Minnesota. Harvest volumes closely mirror land ownership percentages unlike other regions of the US. Natural regeneration is the dominant form of regeneration in the NENC region. Planting, and more intensive management only occurs on a small percentage of the landscape, typically less than 10%.

A combination of growth and yield simulations, 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 NENC softwood 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 187 MJ of energy to produce a cubic meter of NENC softwood sawlogs with a resultant Global Warming Potential (GWP) of 13.0 kg CO_2e/m3 of sawlog harvested and loaded on the truck ready for transportation to the mill. This impact is approximately 1.7% of the CO_2e that is contained in a m^3 of NENC softwood sawlogs.

Keywords: *Northeast and Northcentral softwood forestry, softwood LCA, life cycle assessment, environmental footprint, wood products, forest carbon*

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Introduction

This study was designed to provide input data for estimating the environmental footprint of a cubic meter of harvested softwood sawlogs from the Northeast and Northcentral (NENC) region of the US. It synthesizes an array of data 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 NENC 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 requirements of *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 component 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 NENC softwood forests using current data and data allocation processes.

Forest Inventory and Analysis (FIA) data reported every decade by the United States Forest Service is used to provide a general description of the timber resources, and to determine harvest allocations and product outputs from 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, simulation data, 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

The NENC forests generate approximately 7% of the US softwood products, and nearly 60% of U.S. hardwood forest products (Table 1) from 32.1% of US Timberland (Figure 1) (Derived from Oswalt et al. 2019). Nearly 75% of total softwood harvests come from only four states (Maine, Michigan, Wisconsin, and Minnesota) and 88% of total softwood harvests come from these four states plus New Hampshire, New York and Vermont (Table 2).

Table 1 Relative percentage of US production of wood products by forest type and product type for the NENC region.

NENC	Total	Softwood Forest	Hardwood Forest
Saw logs	19%	7%	51%
Veneer logs	6%	0%	54%
Pulpwood	18%	7%	42%
Composite products	39%	4%	95%
Fuelwood	53%	10%	96%
Posts, poles, and pilings	15%	13%	99%
Miscellaneous products	8%	2%	24%
Total	23%	7%	60%

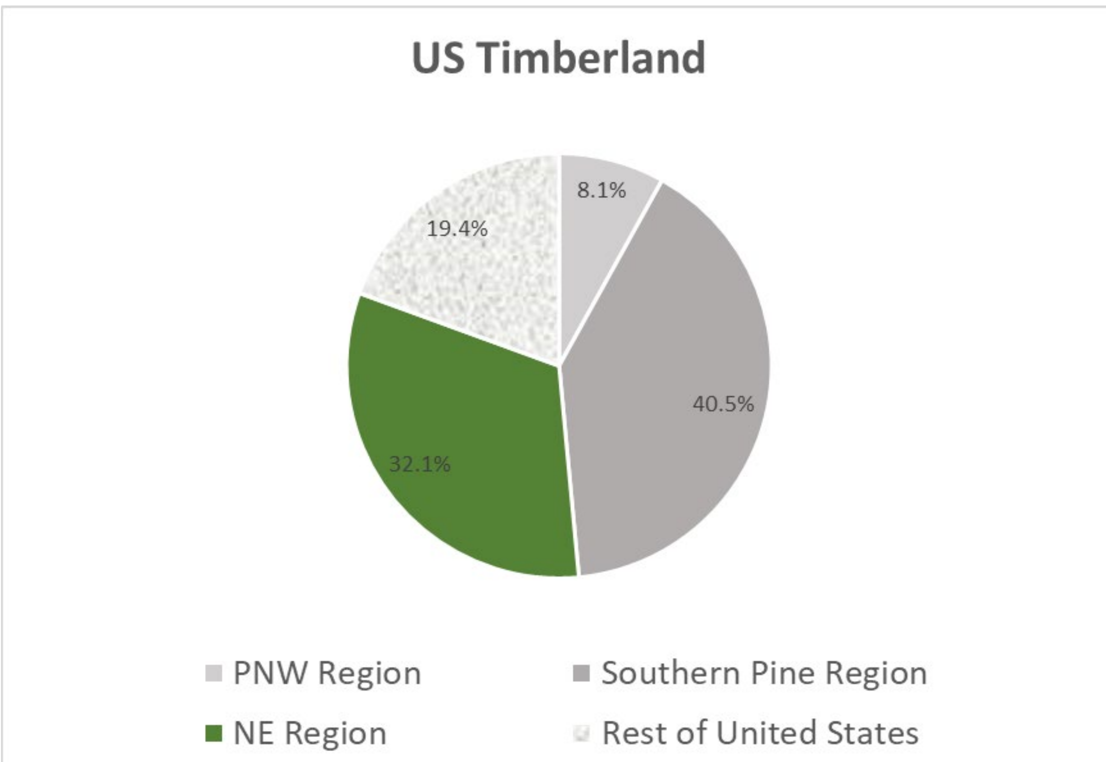

Figure 1: NE Region timberlands as a percent of US total timberlands (includes softwood and hardwood timberlands)

Table 2: Harvest Allocation by State and Subregion. (Extracted from Oswalt et al. 2019)

Subregion	State	Harvest (1,000 ft^3/year)	Percent of Total
Northeast	Maine	224,147	34%
North Central	Michigan	109,961	17%
North Central	Wisconsin	73,320	11%
North Central	Minnesota	70,509	11%
Northeast	New Hampshire	38,529	6%
Northeast	New York	34,641	5%
Northeast	Vermont	26,940	4%
Northeast	Maryland	19,205	3%
Northeast	Pennsylvania	16,396	3%
North Central	Ohio	10,969	2%
North Central	Missouri	8,779	1%
Northeast	West Virginia	7,837	1%
Northeast	Massachusetts	5,307	1%
North Central	Indiana	2,668	0%
Northeast	Delaware	2,363	0%
Northeast	Connecticut	911	0%
North Central	Illinois	689	0%
Northeast	New Jersey	469	0%
Northeast	Rhode Island	169	0%
North Central	Iowa	90	0%
Total		653,899	100%

Most of the harvested softwood volume (79.3%) comes from private lands (93% in the NE, 60.9% in the NC subregions), with the remainder from harvests on other public (state, local, county) (14.6%) and national forests (3.3%) (Ibid.). Harvest volumes closely mirror land ownership percentages unlike other regions of the US. Growing stock has shown only minor upward trends since the early 1950's (Figure 2) based on Forest Inventory and Analysis (FIA) data (Ibid), with most of the increase found in hardwood forests that are outside the scope of this study.

Northeast/Northcentral softwood forests have consistently accumulated more wood volume than is harvested for more than 40 years (Table 3) (Oswalt et al. 2019). Harvest volume is allocated to approximately 51% durable wood products (sawlogs, veneer logs, posts, poles and pilings) or approximately 192,226 MMCF (2016), and the remainder to pulpwood, fuelwood, and other miscellaneous products (ibid). Overall the softwood harvest is allocated 57% to the NE sub-region and 43% to the NC sub-region (ibid).

Table 3: Northeast Softwood Forest Inventory Change 1976-2016 (1,000 cubic feet/year)

	1976	1996	2006	2016
Harvest volume per year	498,576	413,718	353,236	376,915
Net annual growth	1,067,271	646,083	836,486	916,788
Harvest to net growth ratio	47%	64%	42%	41%

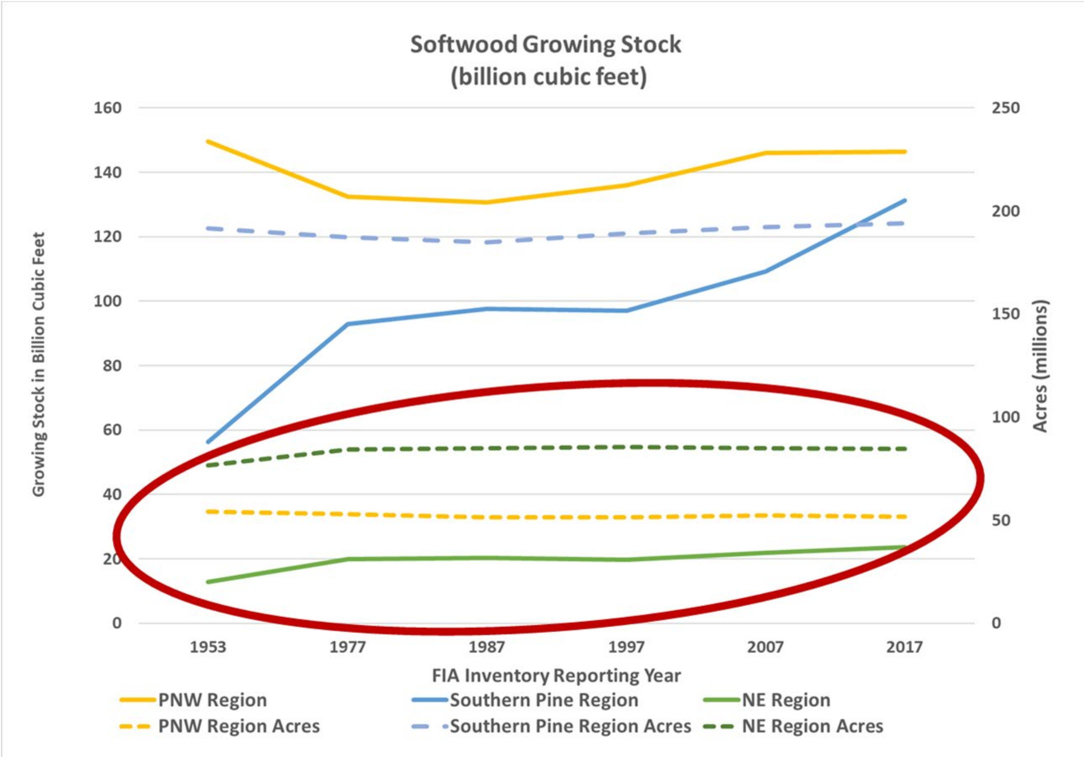

Figure 2 United States softwood growing stock and acreage under production 1953-2017. (Source data [Oswalt et al. 2019](#))

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 NENC 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 NENC 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. Unlike other regions, much of the NENC region relies on minimal silvicultural inputs due to often prolific natural regeneration after partial or clearcut harvests. As such, silvicultural inputs are often limited to weed control and pre-commercial thinning treatments to manage density and forest composition 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). If silvicultural operations do occur, they may include mechanical and/or chemical site preparation, planting, and stand management activities such as pre-commercial thinning and/or chemical or mechanical brushing. No onsite fertilization is reported for NENC 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 durable wood product manufacturing facility, co-products, and waste including forest residues.

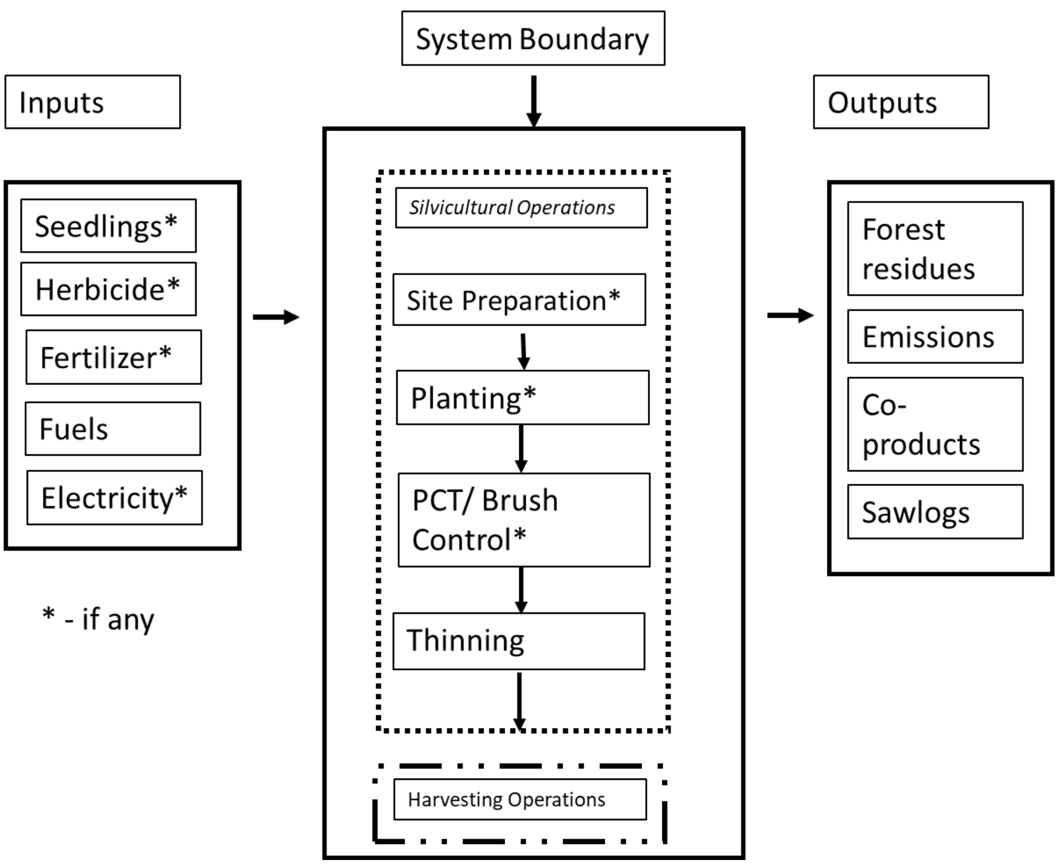

Figure 3: System boundary for the northeast/northcentral forest resources LCA

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 pulp fiber or for bioenergy, 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 NE region, burning forest residues is not a common practice and therefore this element is not included as part of this 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 NENC 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, simulations, and prior datasets were combined to develop this cradle-to-gate LCA of forestry operations for softwood forests grown for the production of durable wood products in the NENC region of the US.

Data Development

Allocation

No primary data using time motion studies or similar methods were collected for this project. A subset of the data by Luppold and Bumgardner (2018) covering states within the NENC region were used to develop allocation percentages for silvicultural and harvesting operations. Luppold and Bumgardner (2018) used FIA data to assess the relative occurrence of different harvest types across the NENC region. Their analysis was able to characterize and quantify the relative percentage of partial cut (PC), clearcut (CC), and thinning (CT) operations across a broad geography by forest type and major species group removal (softwoods versus hardwoods). Those data were used to generate the allocations for softwood harvest volume by area and basal area removed for the NENC region (Table 5). The area and volume allocations were used to estimate the relative percentage of different silvicultural and harvesting operations that are incorporated into the LCIA.

Table 5 Allocation of softwood harvest volume by treated area and basal area removed

% Allocation by Treatment Type	Partial Cut	Clearcut	Thin
By area	80.5%	10.8%	8.6%
By basal area (BA) removed	67.4%	20.2%	9.5%

Table 5 indicates that the majority of forest operations, by area and volume, utilize a partial cutting strategy which is hereafter identified as the “common practice” scenario, that also includes commercial thinning operations. An ‘industrial management” scenario was modeled based on input data estimated from publicly available sources on industrial management. As most clearcut harvests occur on industrial, investor, or large private (>1000,000 acres) forest lands (Maine DACF 2019) all clearcut harvesting area and clearcut harvesting volume was allocated to the industrial management scenario.

Silvicultural Operations Scenarios

The common practice scenario modeled for this project represents common forest management practices in Maine, the most significant softwood sawlog producer in the NENC region. It includes natural regeneration and minimal silvicultural inputs beyond pre-commercial thinning (PCT) and liberation cutting to improve growth on understory trees (Table 6). Precommercial thinning of spruce and fir trees uses crews with brushsaws to reduce stocking and improve spacing. During PCT trees are left on-site as the extraction of these small diameter trees is not economically feasible. All other stand entries remove at least some marketable products. Spruce-fir "rotations" are approximately 60 to 80 years when managed using this common practice. This representative scenario is generated for a final PC at age 72.

Table 6: Silviculture Model for Common Practice Scenario

Northeast region "common" practice model scenario	
Prescription/year	**Product Type**
Natural, advance regeneration; year 0	
Precommercial thinning (PCT); year 10-16	No utilization of thinned trees
Commercial thinning; year 42	Mostly pulpwood
2-stage shelterwood method of regeneration: establishment cut; year 57	Pulpwood, some small-sized sawlogs
Partial removal cut; year 72	Pulpwood & sawlogs

Clearcut harvesting occurs on only 10.8% of forested acres (Luppold and Bumgardner 2018). This harvesting system may also rely on natural regeneration to re-establish the forest, but often is planted to ensure adequate stocking of the desired species. More intensive management is much less common, though a large industrial landowner that produces an estimated 7.3% of all softwood timber in the state of Maine (1.5% of NENC production) does incorporate intensive management on some acres. Using publicly available information for these industrial operations (Irving, 2017, Irving 2020), representative treatments and yields for intensive management including site preparation, planting, brushing, and pre-commercial thinning were developed as inputs for a silvicultural operations LCIA for industrial management practices (Table 7). Data in Table 7 are reported to shareholders and are incorporated into sustainability analysis and annual allowable cut calculations used to maintain forest certification status. As such they are likely representative of 'on-the-ground' practices for the region.

Table 7: Silvicultural Operations for "industrial management" scenario

Industrial Management Scenario Allocations	
	percent of harvested area treated
Pre-commercial Thinning (PCT)	3%
Chemical Brushing and Weeding (CBW)	53%
Manual Brushing and Weeding (MBW)	26%
Site preparation (SP)	31%
Planting (PLT)	32%
Natural Regeneration (NR)	68%

For the LCIA, a weighted average of the common practice and industrial management scenarios were developed to estimate a "representative stand condition" for input to the SimaPro model. As this representative stand condition is 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 NENC 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.

Harvest Operations

In both scenarios, data on forest harvesting operations were derived from common logging equipment configurations developed in spreadsheet models updated by Weiskittel et al. (2017). These spreadsheet models were based on a series of studies for the NE region, including Benjamin (2014), Benjamin et al. (2013), Hiesl (2013), Hiesl and Benjamin (2013, 2014). Variability around these input parameters were developed from recent survey data for the NE region (Quinn et al. 2020) to create estimates of uncertainty.

Results and Discussion

Management, Harvest, and Yield Summary

Data on growth, yield, and management activities representative of 'common practices' were developed by Weiskittel et al. (2017) using growth and yield simulation modeling. Modeling estimates were documented and compared to actual inventory under different forest management and tree utilization scenarios using the spruce-fir forest type in Maine as representative of the NENC region. There is wide variability among stands due to variability in starting conditions. More details on specifications of the common practice modeling simulations, including variability, are found in Appendix 1.

The growth and yield modeling, coupled with updated data on harvest productivity, were used to generate input data for LCIA modeling of a "common practice" scenario for spruce-fir forests. Scenarios based on management and tree utilization according to the common practice were used to estimate outputs for each commercial harvest, including harvested wood yield by product type (Table *8*). This common practice scenario, which includes three stand entries is estimated to yield 274 m^3/ha by age 72 or 3.8 m^3/ha/year.

Table 8 Yield in cubic meters (m^3) per hectare (ha) for NE region softwood forest harvests under common practice scenario.

Prescription/year	Yield			
Natural, advance regeneration; year 0	Sawlogs		Pulp logs	
Precommercial thinning (PCT); year 10-16	m^3/ha	%	m^3/ha	%
Commercial thinning; year 42	27	18%	58	49%
2-stage shelterwood method of regeneration: establishment cut; year 57	65	42%	15	13%
Partial cut; year 72	63	40%	45	38%
Total Yield over 72 years	156	100%	118	100%
Total Yield normalized to 100 years	216	57%	164	43%

Normalized data from Table *8* and Table *9* are consistent in their estimate of 380 m^3/ha over 100 years from natural regeneration and PCT alone. Increasing management intensity through site preparation, planting, and stand management activities can increase that yield to 600 m3/ha at 100 years (two 50 year rotations), or to 828 m^3/ha at 100 years if genetic improvements are realized (Table *9*). These yield increases represent 68-218% improvement over common practice.

Table 9 Yield in cubic meters (m^3) per hectare (ha) for NE region softwood forest harvests under intensive practice scenario.

Intensive Management Scenario Allocations		
	Expected Yield Increase	Expected Yield (m^3/ha) at year 50
Natural Regeneration	-	100
Pre-commercial Thinning (PCT)	90%	190
Planting (PLT)	+300% - 414%*	300 - 414
Total Yield normalized to 100 years		380-828

*includes site preparation, CBW, MBW, PCT (300%) and improved tree genetics (414%)
CBW = Chemical brushing and weeding
MBW = Manual brushing and weeding
PCT = Pre-commercial thinning

By using these intensive management techniques on about 1/3 of all acres, industrial landowners anticipate reducing their rotation to an average of 60 years, with an overall expected yield of 327 m^3/ha or 5.45 m^3/ha/year for the combined CT and final harvest yield (Irving 2020). This yield includes areas of lower intensity management but also includes some combination of intensive practices (Table *9*) that are expected to result in a three to four-fold increase in yield over a 50 year period (Ibid.).

Life Cycle Impact Assessment

The data generated from growth and yield modeling, publicly available industry reports and FIA demonstrate wide variability in productivity per hectare, management inputs, and rotation age (time to final harvest) across the NENC 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 *9* the representative LCIA results per m^3 of NENC softwood sawlogs are found in Table 10 (absolute basis) and in Table 11 (relative basis). Silvicultural operations inputs and emissions reflect the estimated 35% yield of sawlogs on a representative hectare after all entries (Maine DACF, 2019), with the remaining 65% of silvicultural operations allocated to pulp and other co-products (biomass and firewood usually). Almost all of the LCIA impacts of a representative m^3 of sawlog are attributable to harvesting operations (Table 11) which is consistent with minimal silvicultural investment that is common to the region.

Table 10 LCIA result summary for one cubic meter of NENC softwood sawlog for silvicultural operations and harvesting operations. Sawlogs represents 35.2% of the volume per hectare. (Absolute values)

Impact category	Unit	Silvicultural operations	Harvest operations	Total
		per m^3 of sawlog		
Ozone depletion	kg CFC-11 eq	1.96E-09	5.50E-08	5.70E-08
Global warming	kg CO2 eq	2.79E-02	1.30E+01	1.31E+01
Smog	kg O3 eq	6.27E-03	5.64E+00	5.64E+00
Acidification	kg SO2 eq	2.48E-04	1.78E-01	1.79E-01
Eutrophication	kg N eq	5.56E-05	1.09E-02	1.10E-02
Carcinogenics	CTUh	6.63E-10	1.95E-07	1.96E-07
Non carcinogenics	CTUh	5.79E-09	1.90E-06	1.91E-06
Respiratory effects	kg PM2.5 eq	8.68E-06	3.71E-03	3.71E-03
Ecotoxicity	CTUe	1.64E-01	3.61E+01	3.62E+01
Fossil fuel depletion	MJ surplus	6.89E-02	2.60E+01	2.61E+01

Table 11 LCIA result summary for one cubic meter of NENC softwood sawlog for silvicultural operations and harvesting operations. Sawlogs represents 35.2% of the volume per hectare. (Relative values)

Impact category	Unit	Silvicultural operations	Harvest operations	Total
		per m^3 of sawlog		
Ozone depletion	kg CFC-11 eq	3.4%	96.6%	100.0%
Global warming	kg CO2 eq	0.2%	99.8%	100.0%
Smog	kg O3 eq	0.1%	99.9%	100.0%
Acidification	kg SO2 eq	0.1%	99.9%	100.0%
Eutrophication	kg N eq	0.5%	99.5%	100.0%
Carcinogenics	CTUh	0.3%	99.7%	100.0%
Non carcinogenics	CTUh	0.3%	99.7%	100.0%
Respiratory effects	kg PM2.5 eq	0.2%	99.8%	100.0%
Ecotoxicity	CTUe	0.5%	99.5%	100.0%
Fossil fuel depletion	MJ surplus	0.3%	99.7%	100.0%

The cumulative energy demand for the representative m^3 of sawlogs is shown in Table 12 on an absolute basis and in Table 13 on a percentage basis. Energy use was dominated by non-renewable fuels used during final harvest of the merchantable sawlog (99.7%) (Tables 12 and 13). On average, it takes 187 MJ of energy (Table 12) to produce a representative m^3 of NENC softwood sawlogs loaded at the landing and ready for transportation to the manufacturing facility. To produce those sawlogs 13.1 kg CO_2e are emitted, along with other chemical equivalents as shown in Table 10. These results reflect the inputs and emissions for the production of sawlogs only, as pulp logs leave the system boundary as co-products, either during commercial thinning or at final harvest. While silvicultural operations are responsible for a higher percentage of some energy types (Table 13), collectively these other energy types make up less than 0.2% of total energy demand.

Table 12 Cumulative Energy Demand one cubic meter of NENC softwood sawlog for silvicultural operations and harvesting operations. Sawlog represents 35.2% of the volume per hectare. (Absolute basis)

Impact Category	Unit	Silvicultural operations	Harvest operations	Total
		per m³ of sawlog		
Non renewable, fossil	MJ	5.35E-01	1.86E+02	1.86E+02
Non-renewable, nuclear	MJ	1.87E-02	5.39E-02	7.26E-02
Non-renewable, biomass	MJ	7.10E-05	7.18E-06	7.82E-05
Renewable, biomass	MJ	5.50E-03	3.01E-01	3.06E-01
Renewable, wind, solar, geothermal	MJ	3.98E-04	1.70E-03	2.10E-03
Renewable, water	MJ	1.18E-03	6.72E-03	7.89E-03
Total	MJ	5.61E-01	1.86E+02	1.87E+02

Table 13 Cumulative Energy Demand one cubic meter of NENC softwood sawlog for silvicultural operations and harvesting operations. Sawlog represents 35.2% of the volume per hectare. (Relative basis)

Impact Category	Unit	Silvicultural operations	Harvest operations	Total
		per m³ of sawlog		
Non renewable, fossil	MJ	0.3%	99.7%	100.0%
Non-renewable, nuclear	MJ	25.8%	74.2%	100.0%
Non-renewable, biomass	MJ	90.8%	9.2%	100.0%
Renewable, biomass	MJ	1.8%	98.2%	100.0%
Renewable, wind, solar, geothermal	MJ	19.0%	81.0%	100.0%
Renewable, water	MJ	14.9%	85.1%	100.0%
Total	MJ	0.3%	99.7%	100.0%

Variability and Uncertainty

Uncertainty and representativeness analyses are required under the North American PCR (UL 2019) for all modules of an EPD. Based on geography alone, NENC softwood forests exhibit substantial variability in productivity and species composition. Forest Inventory and Analysis (FIA) data (Oswalt et al. 2019) were used to categorize that broad geography into a reasonable set of representative cases for softwood forestry production. Those data provided harvest allocations by state and major species group. Allocations were further refined based on data from Luppold and Bumgardner (2018) to derive estimates of harvest type (partial cut, clearcut, and thinning) by sub-region. Details on common practices were derived from prior research products for the region (Weiskittel et al. 2017). They were augmented by publicly available data on industrial practice (Irving 2017, 2020) and allocations between landowner types (Michigan DNR, 2018, Maine DACF, 2018, 2019) to arrive at a representative allocation between silviculture scenarios.

As most of the LCIA for all indicators is driven by harvest operations, a closer examination of the variability in harvest system efficiencies was conducted. Table 14 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 NENC. This uncertainty estimate incorporates differences in productivity between harvest systems (e.g., cut-to-Length (CTL) versus conventional equipment), and the variability inherent across sites for a given system. Seven combinations of system and productivity were compared based on input data from Weiskittel et al. 2017. Uncertainty estimates do not include allocation and therefore the average is not the same as the harvesting impacts reported in Table 10.

Table 14: 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	11.59	13.21	14.84
		per m^3 sawlog for harvest system operations		
Cumulative Energy Demand (LHV)	MJ	166	189	211

Biogenic Carbon

A m^3 of bone dry logs is estimated to contain 210 kg carbon or 770 kg CO_2e (Puettmann, 2019). On average, silvicultural operations represent 0.2% of the GWP of sawlog production (Table 11) at 0.028 kg CO_2e/m^3. The total GWP/m^3 for silvicultural and harvesting operations is estimated at 13.1 kg CO2e which translates to a ratio of **emissions from silvicultural and harvesting operations (EPD Module A1) to sequestered CO_2e in the sawlog of 1.7%.** These values are calculated using the formula:

GWP per m^3 /kg CO2e stored per m^3 x 100 to express the ratio as a percent.

For those hectares with more intensive management, the upper range of silvicultural impact of 0.11 kg CO_2e per m^3 divided by 770 kg CO_2e in that m^3 of sawlog produces a ratio of: 0.11/770 x 100 = 0.01%

Differences from Prior NENC 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 in Table 15. In Oneil et al. (2010) the LCIA included three general cases for softwood forest management: including low intensity, moderate intensity, and high intensity. Average volume per ha in their base case (275 m3/ha) is similar to the common practice estimate (274 m3/ha) for this study with similar estimated rotation ages (65 years versus 72 years). Percentage differences by impact category shown in Table 15 vary from 4-29% though absolute differences are small (less than 1 unit of any given impact category/m^3 of roundwood). For comparison purposes, data in Table 15 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 access to higher quality data on forest growth and yield in this study, additional information on alternatives to common practice, more detailed information on allocation between products, and greater detail on upstream processes that contribute to overall environmental footprint.

Table 15 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	7.21E-08	6.06E-08	-16%
Global warming	kg CO2 eq	1.22E+01	1.31E+01	7%
Smog	kg O3 eq	5.21E+00	5.65E+00	9%
Acidification	kg SO2 eq	1.61E-01	1.79E-01	11%
Eutrophication	kg N eq	1.27E-02	1.11E-02	-13%
Carcinogenics	CTUh	2.15E-07	1.97E-07	-8%
Non carcinogenics	CTUh	2.02E-06	1.92E-06	-5%
Respiratory effects	kg PM2.5 eq	3.22E-03	3.73E-03	16%
Ecotoxicity	CTUe	5.15E+01	3.65E+01	-29%
Fossil fuel depletion	MJ surplus	2.53E+01	2.62E+01	4%

Data Quality

Data quality parameters relevant to the LCIA are summarized in Table 16. These parameters include data source, geography, and age.

Table 16: Data Quality for Raw Material Inputs

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

Conclusions

Most of the LCA impact for NENC softwood sawlog production comes from harvest operations as silvicultural inputs are minimal. Equipment systems vary by management intensity with combinations of cut-to-length and conventional systems used depending on stand characteristics and volume removal targets. Extensive literature sources were analyzed to develop a range of inputs to the LCI model for the NE region. Results are highly variable depending on assumptions used. ***In comparing the NE region to the southern US region, the LCA footprint is higher per m^3 at harvest, but lower for silvicultural operations.*** Harvest operations result in higher per m^3 impacts due to equipment inefficiencies inherent in partial cutting operations and due to low volume per ha with consequent multiple entries to attain similar volumes that are attained from a single pass system in the US south.

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Appendix 1 – NENC Growth and Yield Estimation

NE Forest Growth and Yield Data and Simulations

Growth and yield modeling estimates of partial cutting on spruce-fir stands was documented and compared to actual inventory in the NE regional analysis under different forest management and tree utilization scenarios for the spruce-fir forest type in Maine that incorporated state of the art modeling for the region. These data were used for a recently completed biomass to energy analysis conducted by CORRIM and were also used as inputs to the current analysis. The growth and yield modeling coupled with experience of the common current practices was used to generate the most realistic input data for LCA modeling of spruce/fire forests to date. Forest growth and yield was simulated under different forest management and tree utilization scenarios for the spruce-fir forest type in Maine. The scenarios were based on management and tree utilization according to the common current practice (whole-tree harvesting with tops and branches of trees left on-site (Hiesl et al. 2016; Leon and Benjamin 2012)) Simulation data were used to estimate live tree carbon stocks over the timeframe of an entire rotation for input into the CORRIM LCA model. The estimated outputs for each commercial harvest, including harvested wood yield (volume, biomass, and C) by product type (e.g., sawlogs and pulpwood) were used to derive the LCIA and LCA for the NE forest region.

Growth and Yield Simulation

Data (USDA 2015a) were assembled from the publicly available Forest Inventory and Analysis (FIA) database (USDA 2015b). Each FIA plot consisted of four, 7.32-m (24.0 ft) fixed-radius subplots spaced 36.6 m (120.0 ft) apart in a triangular arrangement with one subplot in the center (USDA 2015a). All trees with a diameter at breast height (dbh) of at least 12.7 cm (5.0 in) were inventoried on subplots, and trees with a dbh of at least 2.5 cm (1.0 in) were inventoried on one 2.07-m (6.8 ft) fixed-radius microplot within each subplot. Bechtold and Patterson (2005) and (USDA 2015a) provide more complete details regarding the FIA sample design, plot protocols, and data management. Our criteria for selecting subplots included subplots being in the balsam fir (*Abies balsamea* (L.) Mill), red spruce (*Picea rubens* Sarg.), or red spruce-balsam fir forest types, which are within the spruce-fir forest type group (USDA 2015a). All subplots selected for analysis included detailed regeneration measurements (i.e., species and height class). Additional criteria were the presence of a natural regeneration event associated with a cutting treatment. For these subplots, stand attributes at time of inventory (since 2012) confirm the use of heavy partial cutting in Maine. These treatments can be thought of as incomplete removal cuttings in an irregular shelterwood system. Many of the residual trees ≥ 2.5 cm (1.0 in) dbh were not merchantable at time of harvest.

Once data were aggregated, growth and yield of trees on subplots within stands were projected forward over a 100 year simulation period using the Acadian variant of the Forest Vegetation Simulator (FVS-ACD). The initial starting point (i.e., year zero) for the growth and yield projection occurred when a new cohort of trees was established or advance regeneration was released following partial cutting, consistent with FIA field assessment protocols for defining a “regeneration event”. Inventories used to project growth and yield were conducted one to eight years following partial cutting and included detailed regeneration measurements.

Stand projections generated estimates of growth and yield that were then used to estimate the timing of forest management treatments, including liberation cutting, and cleaning treatments, when necessary, once volume or density thresholds were met. When treatments were implemented, all subplots within a given stand condition were treated in the same year. Product values for each subplot were averaged to derive average stand volume, biomass, and C values per stand. Stands were stratified by regeneration status or condition as follows:

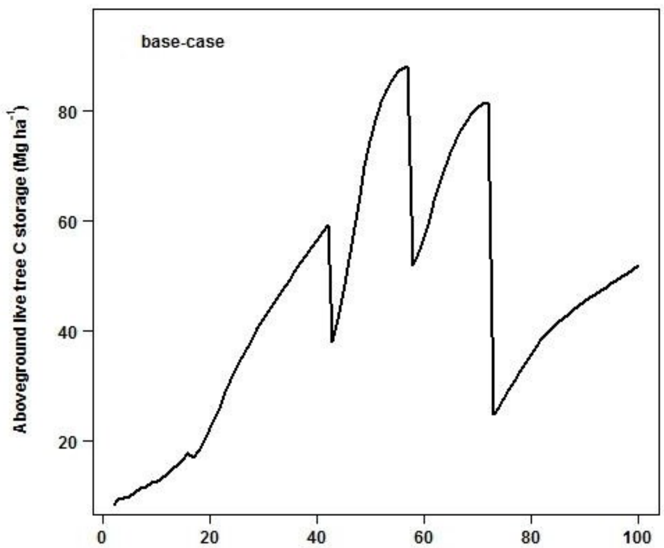
1. Stands that contain advance regeneration of mixed species (softwoods and hardwoods). The softwood component may not meet stocking requirements, so the stands would be managed for multiple species. The new cohort is usually composed of trees with similar heights within stands; over time the stands develop into stratified mixtures. These stands may also contain hold-over trees (i.e., overstory trees that were not removed during the cutting operations when the new cohort was established or released).

2. Stands dominated by softwood advance regeneration. The new cohort is composed of trees with similar heights within stands. These stands may contain hold-over trees.

3. Stands where the younger cohorts vary in height (and likely age) within stands. During cutting operations, different silvicultural treatments may be applied to different areas of the stand.

Outcomes for representative plots with these 3 stand conditions were simulated for the common practice scenario used in this analysis.

Thinning modifiers were utilized in FVS-ACD, including an option to model red spruce and balsam fir growth response to forest management treatments following the methods of Kuehne et al. (2016). Ingrowth features in FVS-ACD were also utilized after the first commercial thinning (Li et al. 2011), although the intent of commercial thinning was not to regenerate the stand but rather encourage growth on residual trees. Tree mortality was modeled with equations in the Northeast variant of FVS (FVS-NE) (Dixon and Keyser 2016). Simulated treatments included precommercial thinning in year 16, commercial thinning (removal of 40% of the stand basal area) in years 42 and 57, and partial cutting in year 72 (leaving a residual basal area of 9.1 m^2 ha^{-1} (40 ft^2 ac^{-1})). These simulations are shown in Figure 4 for the common practice scenario. Figure 5 and Table 17 include stand metrics and growth trajectory for the range of condition classes assessed for variability analysis.

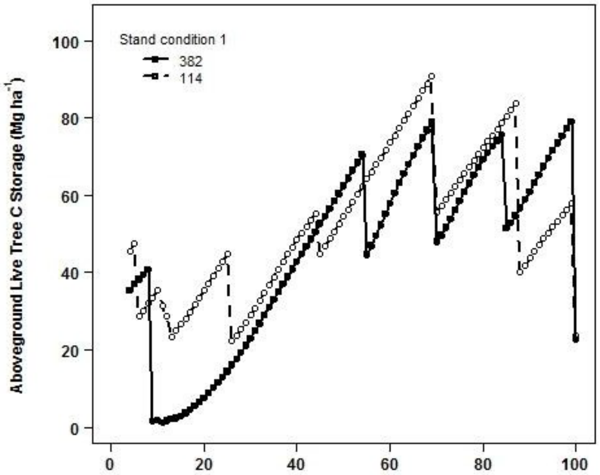


Years Since Stand Initiation

Figure 4 Aboveground live tree C storage (Mg ha-1) for the average "common practice" scenario

Table 17 Mean basal area (BA) and trees per acre (TPA), and quadratic mean diameter (QMD) of stands (FIA plots) used in simulations of growth and yield.

		Trees ≥ 1.0 in dbh			***Trees ≥ 5.0 in dbh***		
FIA plot	Subplots (*n*)	BA (ft^2 ac^{-1})	TPA	QMD (in)	BA (ft^2 ac^{-1})	TPA	**QMD (in)**
114	4	98	591	5.5	88	217	**8.6**
382	4	56	327	5.6	50	102	**9.5**
790	1	93	1392	3.5	42	193	**6.3**
1990	2	22	234	4.2	19	84	**6.4**
2065	4	64	789	3.8	27	114	**6.5**
2159	**4**	**58**	**3497**	**1.7**	**16**	**48**	**7.8**



Years Since Stand Initiation

Figure 5 Aboveground live tree C storage (Mg ha-1) for common practice scenarios by stand condition.

Description of Metrics for Stand Level Simulations – Variability Assessment

Live Tree C: Species and diameter at breast height (dbh) were used to calculate live tree oven- dry biomass using “complete tree” allometric regression equations (Young et al. 1980). These predicted biomass values included aboveground and belowground portions of trees excluding fine roots (Young and Carpenter 1967). Biomass was converted to C content using species- specific C concentration estimates (Lamlom and Savidge 2003). These values were used to derive the average live tree C stock for each stand. Live tree biomass above a 15.2-cm (6-in) stump for trees ≥ 2.5 cm (1 in) dbh and above the root collar for smaller trees were also estimated using equations developed by Young et al. (1980).

On-site woody materials: Woody biomass in the tops of trees and branches including fine woody materials typically left in the woods or on the landing. For trees 15 cm (6.0 in) dbh and larger the upper diameter limit of the bole segment was 10 cm (4.0 in); for smaller trees the upper limit was 2.5 cm (1.0 in) or equal to the base of the larger branches present. This category was limited to trees cut for commercial products.

Volume: Cubic foot volume per acre including wood and bark for pulpwood and sawlogs (wood only could be supplied). Derived using taper equations and a segmentation approach (Li et al. 2012).

Biomass: Oven-dry biomass (Mg ha^{-1}). This includes wood biomass (i.e., without bark) for pulpwood and sawlogs, and wood and bark biomass for on-site woody materials. Miles and Smith (2009) specific gravity values were used in the pulpwood and sawlog calculations; Young et al. (1980) biomass equations were used for on-site woody materials. Biomass was converted to C content using species-specific C concentration estimates (Lamlom and Savidge 2003).