Carbon Life Cycle Assessment on California-Specific Wood Products Industries: Do Data Backup General Default Values for Wood Harvest and Processing?

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Abstract: Carbon life cycle assessments (C LCA) play a major role in greenhouse gas (GHG)-related forest management analytics for wood products and consist of several steps along a forest to disposal path. Yet, input values for wood product C LCAs frequently rely on potentially outdated generic datasets for wood product outputs and mill efficiencies. Assumptions regarding sawmill efficiencies and sawmill-specific wood product outputs have a direct and significant impact on wood product C LCAs because these variables affect the net carbon footprint of the finished product. The goal of this analysis was to evaluate how well standard wood product C LCA inputs and assumptions for the two initial wood products LCA steps (i) forest operations and (ii) wood processing represent the current state of the wood processing industry in California. We found that sawmill efficiencies and wood product outputs both support and deviate from lookup tables currently used in publications supporting the climate-forest policy dialogue. We recommend further analysis to resolve the major discrepancies in the carbon fraction stored in durable wood products and production-related emissions to improve C LCA metrics and advance forest-related climate policy discussions in California and elsewhere.

Keywords: carbon life cycle assessment; wood products; forest industry; California

1. Introduction

Carbon stored in wood products plays a major role in greenhouse gas (GHG) related forest management analytics such as required for national GHG inventories [1], forest carbon offset markets [2], GHG impact analysis of forest management options [3,4], or quantifying nature-based climate solutions [5]. Wood product carbon inputs frequently rely on standardized inputs that might be outdated. Carbon life cycle assessments (C LCA) for wood products consist of several steps along a cradle to grave path: fossil fuel emissions related to harvest and in-forest processing activities, transportation to a manufacturing facility such as saw or paper mill, fossil fuel emissions and product groups manufactured at the processing site (including fossil fuel offsets by using mill residues for energy production), transportation to and from distribution centers, in-use (e.g., half-life of products) and post-use GHG emission profiles (e.g., energetic use, deposition fate, non-CO \(_2\) emission profiles), and displaced fossil fuel intensive non-wood products (e.g., concrete, steel, aluminum). Carbon dioxide (CO\(_2\)) emissions can be used as a standardized metric for mass-balance equations. If non-CO\(_2\) GHG emissions are anticipated or stored carbon is reported on, CO\(_2\) equivalents (CO\(_2\)e) can be used to further extend this standardization metric.
Assumptions on sawmill efficiencies and sawmill-specific wood product outputs have a direct and significant impact on wood product C LCA outcomes and the GHG footprint of the finished product. The accuracy of these assumptions impacts the in-use and post-use C LCA profiles for wood products. However, input values for wood product C LCAs frequently rely on generic datasets on wood product types and mill efficiencies for a given region, as well as product use lifespan and post-use fates that are likely outdated. For example, data predating 2006 [6] are frequently cited in harvested wood C LCA analyses. During the last 30 years wood producers and manufacturers have been under competitive market pressure, which has led to persistent incremental changes to the efficiency of wood manufacturing facilities and forest harvesting technology. The changes in these industry sectors requires a periodic review of such datasets to capture their current performance profiles.

The goal of this analysis was to evaluate how well standard wood product C LCA inputs and assumptions up to and including the manufacturing facility (Figure 1) represent the current state of the wood processing industry in California. In 2016, the closest date for which state-wide statistics are available, California’s timber harvest was 5.910 million m$^3$ which was processed at 80 different processing facilities [7].

![Figure 1. Carbon LCA boundary of study.](image)

2. Materials and Methods

In 2016, we surveyed three large commercial sawmill owners who process sawlogs from their own as well as public timberlands at 11 sawmill sites. The primary reporting unit for sawlogs and processed lumber is a thousand board feet (mbf) in the US. One board foot equals a volume of a one-inch (0.0254 m) thick board with a length of one foot (0.305 m). Board feet expressed in "lumber tally" are actually produced volumes while "log scale" is an estimate of anticipated board foot volumes produced based on pre-defined algorithms such as set forth in the Scribner log scale [8]. Since the purpose of the study was to test standardized inputs and assumptions, all inputs relied on manual entries and no LCA database or program was used. Conversions from mbf to m$^3$ were based on a conversion...
factor of 3.76 m$^3$/mbf which in turn was based on a dataset-wide average specific gravity of 0.382 mg/m$^3$. We gathered the following 2015 data:

- Sawmill operations—Data were provided in Scribner log scale by dominant species for all participating sawmills. Sawmill wood products (lumber tally for lumber; tonnage and moisture content for all other products) and on-site energy production and consumption was also provided. A small fraction of the sawmill data (5% of lumber volume) was derived from 2014 data;

- Harvest and in-forest processing—Data were provided on usage rates for fossil fuel (diesel and gasoline) engines for chainsaws, yarders, loaders, etc., in gallons/mbf and forest-to-mill production (number of loads, total fossil fuel consumption, average distance) was calculated as averages based on averaged metrics provided for 83% of the dataset. Another subset of the harvest data constituting of 15% of total processed sawlogs provided forest stand-level fossil fuel engine consumption for harvest and processing equipment, harvest area (in ha), slash fate if left on site, number of truck loads (forest to mill), and transport distance.

We used the following conversion factors to change each process variable to megagrams of carbon dioxide equivalents (mg CO$_2$e) to perform GHG calculations. One megagram is equivalent to a metric tonne.

- For fossil fuel emission factors: 0.00232 mg CO$_2$e/liter for gasoline and 0.0317 mg CO$_2$e/liter for diesel fuel [9] and 0.0042 mg C/MWh for natural gas [10];
- 90% efficiency when converting natural gas to process heat;
- For electricity generation from mill and forest harvest residues, we assumed a heating value of 18.5 Gigajoule per oven-dried mg (ODT) [11] and an electrical conversion efficiency of 29% as reported by the major participant of the sawmill survey;
- To calculate avoided emissions from biomass-based electricity generation, we assumed each unit of electricity generated would offset one unit of grid based electricity which had an associated emission factor of 0.205 mg CO$_2$e/MWh for California in 2016 [12];
- A carbon fraction of 0.5 for biomass (0% moisture) which is representative for temperate conifer forests [1]. Specific gravity for wood species was taken from Miles & Smith (2009) [13].

3. Results and Discussion

3.1. Carbon Footprint of Wood Products Manufacturing

For the calendar year 2015, the surveyed entities processed a total of 3.764 million m$^3$ in sawlogs (as shown in Table 1), equivalent to a total of 4.4 million mg CO$_2$e. This included 3.823 million m$^3$ in lumber products storing 2.6 million mg CO$_2$e. Durable byproducts (e.g., paper, pulp, particle board) stored 0.333 million mg CO$_2$e while 0.393 million ODT of short-lived byproducts (sawdust, hogfuel, shavings, bark, pulp chips sold for landscaping, animal bedding, soil amendment, etc.) stored 0.720 million mg CO$_2$e. Biomass sold for energy used off-site (0.191 million ODT) avoided emissions of 0.321 million mg CO$_2$e. An additional 0.274 million ODT of biomass was used on-site for process heat and electricity generation and avoided 0.503 million mg CO$_2$e in emissions. Forest harvest residues (“slash”) included around 0.957 million ODT. While most of this biomass was burnt on-site or scattered in the forest, around 0.266 million ODT were shipped to power plants and results in 0.081 million mg CO$_2$e in avoided fossil fuel emissions.
Table 1. Fate and CO₂ profile of sawlogs processed by surveyed entities in 2015. CO₂ volumes stored in wood products do not add exactly to 100% of CO₂ volume of harvested sawlogs due to rounding and minimal reporting inconsistencies (4% error). The quantity of CO₂e is reported in millions of megagrams (10⁶ mg). Carbon stocks and GHG emissions are expressed as positive values. GHG emission savings are expressed as negative values.

| Category                                          | Production/Processing Unit | Value 10⁶ mg | CO₂e 10⁶ mg |
|---------------------------------------------------|-----------------------------|--------------|-------------|
| Harvested timber on trucks to mill                 | 10⁶ m³                      | 3.764        | 4.387       |
| Slash                                             |                             |              |             |
| Scattered on site                                  | 10⁶ ODT                     | 0.492        | 0.902       |
| Onsite open pile burning                           | 10⁶ ODT                     | 0.199        | 0.347 a     |
| Used for electricity                               | 10⁶ ODT                     | 0.266        | −0.081      |
| Lumber mill products                               |                             |              |             |
| Lumber                                            | 10⁶ m³                      | 3.823        | 2.633       |
| Byproducts, durable (pulp, paper, particle board)  | 10⁶ ODT                     | 0.182 b      | 0.333       |
| Byproducts, short-lived, non-energy                | 10⁶ ODT                     | 0.393        | 0.720       |
| Byproducts, hog fuel sold offsite for energy c     | 10⁶ ODT                     | 0.191        | 0.321       |
| Byproducts, hog fuel used onsite for energy        | 10⁶ ODT                     | 0.274        | 0.503       |
| Energy use for in-field processing and transport   |                             |              |             |
| Harvest (logging, yarding, in-forest processing, loading) | 10⁶ L (91% diesel, 9% gasoline) | 44.921 | 0.120       |
| Slash processing and transport                     | 10⁶ L (diesel)               | 18.704       | 0.051       |
| Transport to sawmill (log trucks)                 | 10⁶ L (diesel)               | 8.044        | 0.022       |
| Energy use for sawmill operations                  |                             |              |             |
| Fuel combustion onsite for heat and electricity    |                             |              |             |
| Natural gas                                       | 10⁶ MWh                     | 72           | 0.013       |
| Hogfuel-own                                       | 10⁶ ODT                     | 1906         | 0.503       |
| Hogfuel-purchased                                 | 10⁶ ODT                     | 525          | 0.139       |
| Electricity (excluding slash)                      |                             |              |             |
| Onsite generation used at mill                     | GWh                         | 220          | −0.045      |
| Onsite generation sold to grid for use offsite     | GWh                         | 301          | −0.062      |
| Purchased from grid to run mill                    | GWh                         | 63           | 0.13        |

(a) Assuming a pile burn combustion efficiency of 95% [14]. (b) Note: Biomass volume is not equivalent to output volume since products in this category can be of composite nature also including other raw material. (c) Hogfuel: Low-quality (mixed) biomass not meeting other byproduct definitions such as bark, pulp chips, shavings, sawdust.

Fossil fuel emissions associated with harvest and transport (diesel and gasoline) as well as processing at the sawmill (natural gas and grid electricity) equaled 5% and 1% of CO₂e stored in lumber and durable byproducts, respectively. This relatively low proportion is consistent with other recent forest sector C LCA studies [15].

If the on-site electricity production using hogfuel (excluding the slash shipped to a biomass power plant) was appropriately considered to displace fossil fuel emissions, sawmill CO₂e emissions would decrease to 2% of CO₂e stored in lumber and durable byproducts. Only 2% (measured by CO₂e emissions) of sawmill energy demand was satisfied with fossil fuels (natural gas for process heat; on-site electricity generation offsetting almost entirely the need for grid electricity). A total of 520 GWh/year of electricity was generated on-site from hogfuel from the three entities; satisfying 100% of on-site net electricity demand. Of total on-site electricity production, 58% or 301 GWh were sold to the grid and not used on-site. Although on-site electricity production exceeded on-site demand, 13 GWh were purchased in 2015 to bridge peak consumption times when demand exceeded production, resulting in a net of 288 GWh of excess biomass electricity production.

Electricity generation from slash was around 394 GWh derived from 266,000 ODT of biomass; offsetting around 0.081 million mg CO₂e. Pile burning of slash at or near the harvest site emitted around 0.347 million mg CO₂e while scattered slash will emit around 0.902 mg million CO₂e in the short-term due to decay. See section “Slash: fate and fossil fuel use” below for more information regarding slash. No value-added pathway for slash was reported such as biochar [16] or briquetting [17] production.
3.2. Dataset as a Representative Snapshot of the 2015 Timber Industry in California

We collected calendar year 2015 Sawmill data derived from 11 sawmills. As a reference, Marcille et al. [7] counted a total of 32 California-based sawmills operating in 2016. These sawmills process logs sourced from forests in the northern California coastal region as well as mid to high-elevation forests in the northern and central Sierra Nevada and Cascade mountain ranges.

The sawmills surveyed processed a total of 3.764 million m$^3$, which represents over 75% of all harvest volume from private and tribal lands in 2015. The dataset also represents 60% of the total 6.129 million m$^3$ log harvest in California during 2015 [18].

The surveyed sawmills processed volumes of trees species that closely resembled the total California specific harvest volume species composition for 2016 [7]. While Ponderosa pine was somewhat overrepresented, Douglas fir was slightly underrepresented (Table 2). Because the lumber conversion rates for Ponderosa pine compared to Douglas fir are similar, we can conclude that from a sawmill data perspective, the dataset was representative of the total harvested volume and sawmill performance in California for 2015.

Table 2. Timber volumes processed—surveyed (2015) vs. total volume (2016) in California.

| Species                   | Surveyed Volumes 10⁶ m³ | % of Total | Total CA Volumes 2016 [7] | % of Total |
|---------------------------|-------------------------|------------|--------------------------|------------|
| Ponderosa pine (Pinus ponderosa) | 1.011                   | 27%        | 1.350                    | 23%        |
| Sugar pine (Pinus lambertiana) | 0.346                   | 9%         | 0.425                    | 7%         |
| Douglas fir (Pseudotsuga menziesii) | 0.793                   | 21%        | 1.394                    | 24%        |
| Redwood (Sequoia sempervirens) | 0.432                   | 11%        | 0.821                    | 14%        |
| Other species             | 1.181                   | 31%        | 1.919                    | 32%        |
| Total                     | 3.764                   | 100%       | 5.358                    | 100%       |

We received fossil fuel consumption data for harvest operations for 91% of the harvested volumes reported in Table 2. For forest-to-sawmill transport, we received data on mileage for 91% of the total volume and fossil fuel consumption records for 83% of the dataset. Stand-level detailed harvest data was provided to us for 4000 harvested hectares at 112 harvest sites; yielding 0.334 million m$^3$ or a total of 9% of the total reported volume. In comparison, Stewart & Nakamura [19] derived their dataset from 28 sites covering 6870 hectares in northern California.

3.3. Harvest, Transport and Sawlog Processing Analysis

3.3.1. Harvest Operations

Type of harvest operations and fossil fuel use. Fossil fuel use across entities ranged from 3.9 to 6.8 L per m$^3$ harvested sawlog volume and averaged at 6.6 L per m$^3$ (Table 3). Gasoline, used for some trucks and chainsaws besides diesel, represented around 9% of the total fuel use. The stand-level harvest dataset (4000 hectares, 112 harvest sites; 0.334 million m$^3$) suggested that 45% of volume was harvested using tractor-based logging and 53% using cable-logging systems. Helicopter based logging was minimal (2%) for the stand-level harvest dataset and absent for the other harvest dataset. Fuel use for ground-based systems exceeded reported values from other studies [15,20] by a factor of two. Skyline-based logging systems also exceeded values reported in the literature [15,20].
Table 3. Average and range of fuel consumption recorded (liter per m$^3$ of harvested sawlog volume). Ranges provided in brackets by surveyed entity. Ground-based systems reflect mechanized systems dominated by feller-bunchers, shovel yarders, boom processors, and (truck) loaders. Lubricant consumption was not considered (<1% of fuel use).

| Harvest System | Average and Range for Surveyed Entities | Oneil & Puett-Mann [20]; U.S. Pacific Northwest | Han et al. [15]; Even-Aged Redwoods |
|----------------|-----------------------------------------|-----------------------------------------------|-----------------------------------|
| Ground-based (mechanized) | 8.5 (4.3–8.8) | 3.2 | 4.1 |
| Skyline-based | 4.8 (3.4–5.0) | 3.0 | 3.5 |
| Helicopter | 12.3 (12.1–14.1) | n/a | 17.8 * |
| Weighted average | 6.6 (3.9–6.8) | | |

(a) Uneven-aged use.

Slash: fate and fossil fuel use. Data on slash production was provided for the entire dataset on a per mbf (log scale) basis and averaged by surveyed entity. Slash constituted 29% of total harvested biomass. Slash production varied by entity from 0.24 to 0.35 ODT/m$^3$; averaging at 0.29 ODT/m$^3$. This is double the rate as reported by e.g., Stewart & Nakamura (2012). On average, 28% of slash was used for electricity production, 21% was pile-burnt and 51% was scattered on site. However, slash fate varied considerably between surveyed entities. Some entities scattering 95% of slash while shipping none to power plants and other entities shipped up to 40% to power plants while pile-burning 25%. These slash recovery rates are significantly lower than the slash production rates reported in the literature. For instance, Stewart & Nakamura [19] and Ince et al. [21] assumed slash recovery rates of 75% and 66%, respectively. In-forest processing emissions for slash destined for electricity generation was based on survey responses for 83% of total reported harvest volume and included 3.0 and 3.2 L per ODT for in-forest processing (handling, chipping, loading) and transport to a power plant, respectively. In comparison, Han et al. [15] suggests only 1.5 L per ODT for biomass processing and loading.

3.3.2. Sawlog Transport

Sawlog transport distance (one way) ranged from five to 109 km by entity and averaged 100 km for the entire dataset available for harvest volumes. The log volume transported averaged 16.4 m$^3$/load, and had a range from 16.2 to 18.4 for all entities surveyed. Harvest site to sawmill fuel consumption was only reported directly for 83% of total sawlog volume surveyed and averaged 2.1 km per liter. In comparison, the average fuel economy for a truck of this size (class 8) in 2020 was 2.3 km per liter [22].

3.3.3. Sawmill Processing

Sawmill efficiency. Lumber overrun, the “amount of lumber actually recovered in excess of the amount predicted by the log scale, expressed as a percentage of the log scale” [8] averaged 1.6 and varied from 1.6 to 1.9 across entities. A value >1 means that more lumber was procured than initially estimated. This average value is identical with previously reported averages for California [8]. Sawmill efficiency, measured in the fraction of lumber and durable byproducts divided by processed volume was 67.6% across all surveyed entities. Across-entity variations were minimal with a range of 67.3 to 73.4% of entity-wide (average) sawmill efficiencies. This sawmill efficiency is essentially identical to typical lookup values such as the 67.5% provided by Smith et al. [6] for Californian softwood processing facilities and widely applied for wood product life cycle assessments [23]. It is considerably higher than the 61% suggested for the entire Californian durable wood products processing industry [24]. An industry-wide efficiency of 74.9% as applied by Stewart and Nakamura [19] is not supported by this data. The California timber processing industry’s efficiency applied by Stewart & Nakamura [19] was based on a 2006 California-wide forest product industry survey and has been superseded since then by a 2012 [24] and 2016 [7] survey.

Sawmill energy demand. A total of 82.3% of process heat demand, measured in mg CO$_2$e emissions as a proxy to energy units, was covered by residual biomass internally
sourced during sawlog processing. Another 15.3% was covered by biomass sourced from off-site. Only 2.4% of on-site process heat demand was derived from fossil fuels (natural gas). 100% of net electricity demand was produced internally. Corroborating on-site energy demand for California sawmills is challenging since literature is sparse and is site-specific. A study close to California \[25\] suggests 48 MWh/m$^3$ electricity use while our dataset suggests 74 MWh/m$^3$ of wood products. This higher consumption cannot be further explored due to a lack of data but can potentially explained by more energy-intensive machine processing of lumber and byproducts. Most of the electricity use in Loeffler et al. \[25\] was purchased off-site which might be another driver to keep electricity use low. Comparing other on-site energy use such as for process heat between the two studies provides challenges since both regions differ significantly in their energy production and consumption mechanisms (combined heat and power generation at the California mills with a percentage of biomass bought off-site and a percentage of on-site electricity production sold to the grid vs. a fossil fuel reliant energy demand for the southwestern US dataset).

Wood products output. For reporting, the total durable volumetric product unit outputs from the surveyed sawmills were converted to mg CO$_2$e to calculate their respective conversion rates. The total lumber conversion rate was 71% with another 9% stored in durable byproducts including raw material for paper and pulp. This result suggests considerable deviations from widely utilized lookup tables used for wood product life cycle assessments such as California Air Resource Board’s data for forest-based carbon offset calculations \[23\] which assume that lumber represents 97% to 99% of wood products generated in Californian sawmills with 0% to 1% stored in pulp/paper products and 0% to 3% stored in plywood. In contrast, the dataset more closely aligns with the wood product mix suggested by Smith et al. \[6\] for California which suggests that 67% of total durable outputs is stored in lumber. Where the Smith et al. and our dataset differs is in the fraction of short-lived wood products (landscape mulch, animal bedding, soil amendment, etc.) which constitutes 20% of total non-bioenergy products in our dataset. There is no comparable wood product category available in the Smith et al. \[6\] lookup tables.

4. Conclusions

Carbon LCA inputs and assumptions for wood products as currently used in a California context are generally supported by recent data. We recommend further analysis to resolve in particular the major discrepancies in the carbon fraction stored in durable wood products. Expanding the opportunities of slash for energetic use or other wood products could considerably enhance GHG benefits of the wood products industry. Improvement of production-related emissions and C LCA metrics could advance the climate policy discussion regarding the potential of forests to mitigate GHG emissions in California and beyond.

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Data Availability Statement: Restrictions apply to the availability of these data. Data was obtained from sawmills and are available from the authors with the permission of those sawmills.
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