Final Report
Carbon Accounting of a DNR Timber Sale: Case Study-Forest to Product

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1 Abstract

A case study of likely carbon impacts of forest harvesting and manufacturing was developed using a combination of DNR timber sale cruise data from a mixed stand of second and third growth naturally regenerated stands, scaled harvest volume, trucking data, and other secondary sources. These data were aggregated and then allocated to various downstream products to generate a life cycle impact assessment (LCIA) for the growth and harvesting of a cubic meter of harvested logs from mature second growth and third growth Douglas-fir forests. These LCIA data were included as upstream inputs to wood product models for Washington wood production facilities to generate a cradle to gate LCA of four primary harvested wood products. These primary product LCAs were compared to functionally equivalent alternative wood and non-wood products to estimate substitution benefits from the use of wood derived from this example timber sale. The primary wood product inputs and outputs were scaled to the log volume from the timber sale. Outcomes were compared to a no-harvest alternative on a per acre basis. Results, coupled with assumptions on growth and decay, were also used to generate an estimate of likely carbon outcomes 40 years forward. Some key results when harvesting impacts, manufacturing, product storage, and substitution are included:

- For every acre harvested, an additional 11.71 metric tons of carbon is stored or offset over the no-harvest alternative of an 80 year old forest stand starting in year 0. This full carbon accounting indicates there is no carbon debt, even on a per acre basis, when substitution and leakage effects are accounted for in the analysis.
- As Washington state requires reforestation, future forest growth increases the differential to as much as 72 metric tons/acre by year 40. This result is at odds with other reports that suggest retaining forests that are 80 years and older as carbon sinks, generates a larger carbon benefit than harvesting, while accounting for the harvested wood product, substitution, and reforestation emissions and storage. These differences are partially a result of modeling assumptions about continued, and substantial, forest growth past year 80. Those assumptions are not supported by the Forest Inventory and Analysis (FIA) data (USDA 2023) that was used in this analysis to estimate future growth of regenerating and mature forests.
- Additionally, discounting the carbon stored in forest residues from harvest, and underestimating or ignoring the impacts of substitution are large drivers of the differences reported here, versus those in some model-based literature.

2 Overview

The American Forest Resource Council (hereafter AFRC) requested a full carbon accounting of an example Washington Department of Natural Resources (DNR) timber sale using life cycle assessment (LCA) data on forestry, forest operations, and manufacturing of products that were produced from that sale. The timber sale used for the analysis is the Penny Alderwood Timber Sale, a 235.1 acre (net) harvest in the state of Washington (hereafter the Penny Alderwood Harvest or PAH). This sale includes both second and third growth timber, which allowed for a within sale comparison of the forest resource LCA outcomes. However, full LCA accounting for the harvested wood products and substitution results were based on a weighted average timber harvest volume from PAH as a whole.

Using input data provided by AFRC partners, coupled with extant PNW data on forestry (Oneil and Puettmann 2017) and product manufacturing operations, LCA were generated for four primary products: softwood lumber (Milota 2020) and plywood (Puettmann et al. 2020), poles (CORRIM 2022), and hardwood lumber (CINTRAFOR 2022). The LCA outcomes from primary products were compared to LCA data from the Athena Impact Estimator for Buildings (Athena 2023) and published LCAs (Puettmann and Salazar 2019, CINTRAFOR 2022) on substitute products to estimate the primary substitution benefits from the PAH. Co-products were tracked as they left the system boundary. The per functional unit estimates were scaled to the PAH level as representative of the carbon outcome of typical DNR timber sale. Summary results for each comparison are found in section 4.

In addition, AFRC requested a comparison to a no-harvest alternative for the second growth (80-year-old forest) inventory. To facilitate those comparisons summary data for the relevant forest types found in the USFS Forest Inventory and Analysis (FIA) for Washington state were synthesized (see Appendix C). Using these synthesized FIA data, an estimated growth trajectory of a no-harvest alternative for the 80-year-old stand was calculated and calibrated to existing PAH sale metrics for bole wood. Estimates of residual aboveground biomass (AGB) and root carbon were calculated with the component ratio method used by FIA, scaled to actual bole wood values for PAH.

The two alternatives were compared to generate their relative carbon benefits at the point of harvest using established LCA methods. These results were coupled with carbon stock and storage estimations from the FIA volume over age curves for the western Washington species analyzed for this case study.

3 Summary Results

3.1 Case Study LCA and Substitution Carbon Summary

The log yield from the Penny Alderwood Harvest (PAH) (Appendix C) was allocated to four primary products: softwood lumber and timbers (Milota 2020), softwood plywood (Puettmann et al. 2020), softwood poles (CORRIM 2022), and hardwood lumber (CINTRAFOR 2022). For this analysis cedar and pulp logs, representing 8% of the mass of timber removed, were not analyzed, and are therefore excluded from the overall comparison. This results in an under-estimate of the carbon benefit of harvest.

Comparisons for the substitution analysis used the Athena Impact Estimator (Athena 2023). Conservative substitutes were chosen. Namely, 1) lumber was compared to steel wall studs rather than steel beams or mass timber components with known higher substitution values; 2) plywood was compared to oriented strandboard (OSB) (Puettmann et al. 2020) without accounting for additional transportation emissions (as OSB is not produced in the PNW); 3) utility poles were compared to steel or concrete poles; and 4) hardwood cabinet lumber (CINTRAFOR 2022) was compared to a similar product made from MDF (medium density fiber board) (Puettmann and Salazar 2019), rather than plastic or metal alternatives with a higher carbon footprint. Substitutions for co-products were not done for this case study. Substitution comparisons are thus likely to represent the worst-case alternatives, rather than the best-case alternatives. As such, the analysis completed herein is more likely to under-estimate the benefits of harvest versus no-harvest alternatives, rather than overestimate them. Using these conservative substitution comparisons, the following points can be made (as summarized in Table 1):

1. Using softwood lumber for wall framing over a steel stud avoids nearly 17 kg of CO2e per meter squared construction from entering the atmosphere. This equates to nearly 15,000 metric tons CO2e over the harvest of PAH allocated to softwood logs only. Considering only the logs destined to construction lumber and large timbers, 15,000 metric tons of CO2 is equivalent to removing 3,251 gasoline powered vehicles driven in one year or heating 1,841 homes for one year[1].
2. Using softwood plywood for wall sheathing over a OSB avoids 0.28 kg CO2e / m2 from entering the atmosphere. This equates to over 100 metric tons CO2e over the harvest of PAH allocated to veneer logs only. Considering only the logs destined to veneer/plywood facilities, 100 metric tons of CO2 is equivalent to removing 22.3 gasoline powered vehicles driven in one year or heating 12.6 homes for one year.
3. Using wood poles over steel or concrete avoids on average 2,217 kg CO2e / pole from entering the atmosphere. This equates to over 1,150 metric tons CO2e over the harvest of PAH allocated to pole logs only. Considering only the logs destined for pole facilities, 1,150 metric tons of CO2 is equivalent to removing 256 gasoline powered vehicles driven in one year or heating 145 homes for one year.
4. Using solid hardwood lumber for a cabinet over an MDF cabinet front avoids on average 0.33 kg CO2e from entering the atmosphere. This equates to 62 metric tons CO2e over the harvest of PAH allocated to hardwood logs only. Considering only the logs processed in hardwood facilities and then destined to cabinet manufacturing, 0.62 metric tons of CO2 is equivalent to removing 14 gasoline powered vehicles driven in one year or heating 7.8 homes for one year. NOTE: there are no MDF plants in Washington, transportation from manufacturing to the Pacific Northwest is out of the scope of this study and would increase the embodied carbon of MDF verses locally produced hardwood lumber. In addition, substituting wood products for other wood products, rarely provide a carbon benefit of one product over their other due to the benefit of carbon storage in all wood products and their relatively low embodied carbon.
5. Using the harvested wood products from the PAH avoids over 16 million kg CO2e which is equivalent to removing 3,529 gasoline vehicles off the road for one year or heating 1,999 homes for one year. (Table 1)
6. The primary products produced from the PAH store over 21 million kg CO2e (5,776 million kg C or 5.8 million metric tons of C). Co-products and those products not analyzed (cedar and pulp logs representing 8% of the mass of the logs harvested from the PAH) are not included, therefore the values noted in Table 1 are conservative.

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[1] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator#results. These estimates are approximate and should not be used for emission inventories or formal carbon emissions analysis.

Table 1 Avoided emissions and carbon stored in products produced from the Penny Alderwood Harvest (PAH).

Wood stud over a steel stud	Plywood over OSB sheathing	Wood pole over average steel and concrete pole	Hardwood cabinet door over MDF	TOTAL
mt CO2e emissions avoided				
14,958	100	1,150	62	16,271
mt CO2e stored in primary product				
16,682	4,045	308	144	21,179

3.2 Comparisons to Case Study Results

3.2.1 No-Harvest Alternative Comparison

When forests are not harvested, the carbon consequences of that decision depend on the system boundary that is evaluated. The most simplistic alternative is to assess a harvest versus no-harvest alternative at the forest level only. That scenario is captured in Figure 1. However, this scenario is incomplete as it does not reflect wood demand dynamics, including the consequences of using alternative materials if wood is not available, or leakage, meaning using wood from other locations to replace the wood that is reserved from harvest. These scenarios are captured in Figure 2.

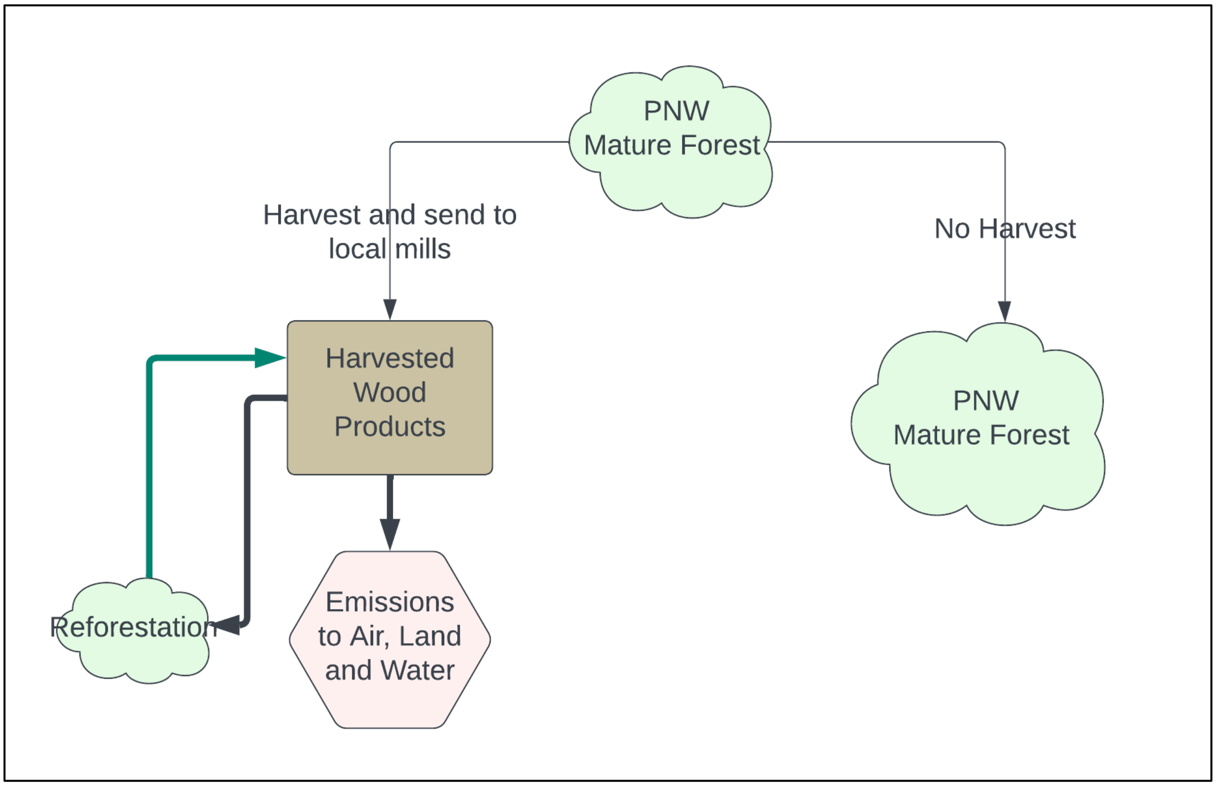

Figure 1: First order carbon consequences of a harvest vs no-harvest alternative.

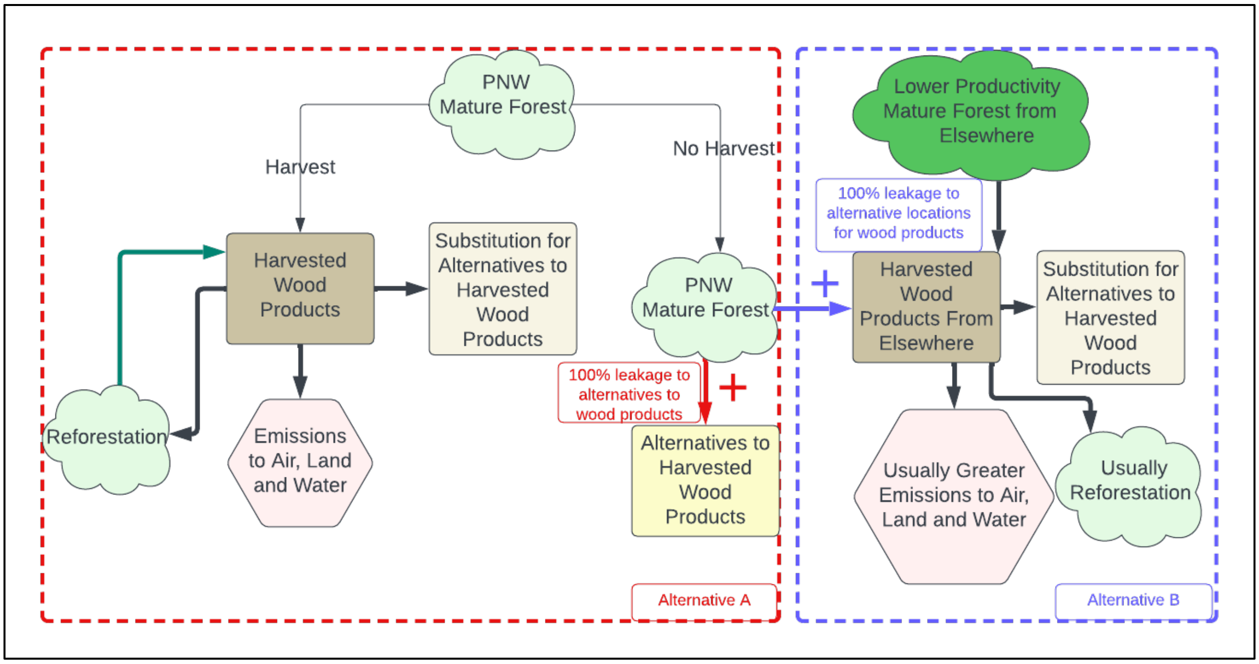

Figure 2: Alternative consequences of no-harvest scenarios where wood demand is met A) with alternative to harvested wood products (red boundary) or B) wood product demand is met in completely different locales (blue boundary) demonstrating 100% leakage.

As atmospheric greenhouse gas reduction outcomes are only relevant at a global scale, the first order effects identified in Figure 1 are too simplistic to achieve measurable results given continued, and increasing, demand for wood products. A more sophisticated approach includes evaluation of one or more alternative pathways as shown in Figure 2. In this study we evaluate the carbon consequences of a harvest versus no-harvest alternative with 100% leakage to alternatives to local wood products (red boundary). Table 2 itemizes the carbon consequences of a harvest versus no harvest alternative for the PAH case study site under this scenario. Detailed descriptions of assumptions and data derivations are provided in the explanatory notes. Scenarios assessing impacts where wood demand was met elsewhere (100% leakage) (blue boundary) were not completed.

Table 2 shows that no-harvest alternatives generate less favorable atmospheric carbon outcomes - on any time horizon - when leakage is considered as compared to harvest alternatives. Case study LCA results, including estimates of product substitution benefits, show harvesting removes an additional 11.7 metric tons/acre over the no-harvest alternative for a representative 80-year old forest stand. Since Washington state requires reforestation after harvest, future forest growth could increase the differential to as much as 72 metric tons/acre by year 40 based on FIA inventory cross validation. Because substitutes for co-products (steel and plastic furniture vs MDF) and minor forest products were not tracked, this carbon benefit is a conservative estimate. This finding challenges the concept of carbon debt, with its payback period that is dependent on the lifespan of the products and the relative growth rates of the regenerating forest. This data driven analysis corrects for the forest growth over-estimates that are typical of process model-based approaches. It also uses market verified LCA approaches to quantify the product, emission, and substitution outcomes from this wood product mix.

Table 2 Carbon Outcomes for Harvest and No-Harvest Alternatives by Component and Change Over Time on PAH

						Explanation
Year since harvest	**0**	**10**	**20**	**30**	**40**	Year since harvest, with 0 being the initial harvest of case study inventory.
	Metric Tons of Carbon per Acre					
Harvested forest: roots and slash remaining; decayed at 2%/decade)	30.81	30.20	29.59	29.00	28.42	After harvest forest residues and roots remain. The values reported are calculated using component ratio methods for forest tops, stumps, and roots calibrated to average removed bole volume for the PAH based on FIA inventory component ratios for stands of comparable age. Decay is estimated at 2% per decade. The values from PAH inventory data are ranked slightly larger than the median value for site class 3-5 and slightly lower than site class 1-2 for the relevant age classes. Those same site classes were assumed for regrowth and extended rotation analysis.
Regenerating forest roots		0.36	2.29	5.43	10.04	Root regeneration from newly established stand based on FIA component ratio carbon estimates for comparable bole volume increases.
Regenerating forest boles/tops/stump		0.00	7.46	21.76	42.32	Above ground biomass increment based on FIA inventory estimates by age class.
Embodied carbon emissions from harvest/ reforestation/ haul/manufacturing	-3.45	0.00	0.00	0.00	0.00	Emissions from year 0 harvest, required regeneration, hauling, and manufacturing emissions. As harvested stands were assumed to be naturally regenerated, no initial stand maintenance emissions were included. This value is the embodied carbon value (i.e. does not include burning wood).
Primary products	24.57	24.57	24.57	24.57	24.57	Stored carbon in primary products - i.e. softwood lumber and plywood, softwood poles, and hardwood lumber.
Substitution benefit of primary products	18.87	18.87	18.87	18.87	18.87	Substitution benefits calculated as the difference in emissions (embodied carbon) from producing primary products versus their alternatives (substitutes) on a functional unit basis, scaled to a per acre volume. See section 4 for detailed analysis and calculations.
Hogfuel and wood fuel burned	-12.87					Includes hogfuel and residues burned during manufacturing as well as a significant portion of the hardwood inputs that were directed to the hogfuel market.
Manufacturing co-products (leave system boundary); decayed at 5% per decade	31.84	30.24	28.73	27.30	25.93	Co-products not burned during manufacturing. These include chips, sawdust, and other materials that are typically utilized for MDF (medium density fiber board), particle board (PB), pallets, and pulp. There was no clear evidence of the ultimate fate of these products in the economic system so they were decayed at 5% per decade as a conservative estimate of loss.
Carbon outcomes of harvest (sum of above)	**89.76**	**104.24**	**111.52**	**126.93**	**150.15**	Net carbon outcome per acre for harvest scenario
Alternative to harvest						
Unharvested 80-year-old forest (trees including roots)	99.14	99.14	99.14	99.14	99.14	Standing inventory estimate of unharvested 80-year-old forest with forest stocking and species mix represented in PAH. Data derived from calibrating harvest inventory bole volume to median FIA inventory bole volume and applying the component ratio method to determine tree top, branches, stump, and root volume. See Appendix B for detailed summary.
Substitution benefit foregone	-21.08	-21.08	-21.08	-21.08	-21.08	As no harvest alternative does not impact demand, assume that demand is filled by substitutes for primary products only, with the value representing their embodied carbon emissions (not the difference between emissions). This provides a conservative estimate of the likely substitution need as co-product substitutes are not included.
Carbon consequences of no harvest alternative	**78.06**	**78.06**	**78.06**	**78.06**	**78.06**	Net carbon benefit of a no-harvest alternative when recognizing the demand impact of substitute products. This does not account for leakage of harvest to other areas.
Comparative Outcomes – difference between no harvest and harvest scenarios	**-11.71**	**-26.19**	**-33.46**	**-48.87**	**-72.10**	The difference between the harvest and no-harvest alternative in metric tons per acre for the PAH sale under the assumptions used above. Negative numbers indicate that no-harvest generates more emissions to the atmosphere than the harvest alternative given the product outputs, emissions, and anticipated substitutes.

3.2.2 Sensitivity Analysis – Log Transport

A hybrid alternative to the red (alternative A) or blue (alternative B) scenario in Figure 2 is to haul raw logs to Washington manufacturing facilities. To assess the impact of this alternative a sensitivity analysis was conducted for hauling softwood sawlogs for lumber production (Table 3). For this sensitivity analysis two alternate assumptions on log transport to manufacturing facilities in Washington were tested. Here, the base assumption is that Washington manufacturers are able to economically access raw log supply from other jurisdictions to meet log demand should a no-harvest alternative be enacted. To simplify and focus the analysis on hauling only, no modeling of differences in yield per acre, forest management activities to produce the needed volume, or time variables to produce the needed volume are included in Table 3. For Table 3 we assumed Aberdeen, Washington as the base case and adjusted the log transport distance (A2) to reflect a location in Oregon and/or transport from the southeast United States. Moving one metric ton of logs by road, 1 km has an embodied carbon impact of 0.11 kg CO2e; by rail it is less. The relevant transportation embodied carbon estimates per ton-kilometer (Table 3), when included in the cradle to grave embodied carbon estimates (excluding differences in forest resource embodied carbon), show a clear increase in impact when roundwood is transported any distance to meet local demand for logs in supply constrained mills. The values in Table 3 are per m3, therefore they would need to be adjusted to a per acre value to be comparable to the results in Table 2. ***NOTE: This analysis considers only the additional carbon impacts associated with transport and does not consider the additional economic impacts burned to wood production facilities. It is the author's belief that technically obtaining resources from outside Washington is possible, it is prohibitive based on cost alone.***

Table 3 Impact of Transport of Roundwood to Aberdeen, WA from Penny Alderwood Harvest, Sweet Home, Oregon, and the Southeast United States.

	BASE – Aberdeen, WA	Sweet Home, Oregon	Southeast, US (Rail)
Embodied Carbon (A2) kg CO2e	11.91	33.51	67.79
Percent increase from Table 4		37%	95%
Embodied carbon A1-A3, kg CO2e	59.10	80.70	114.98

4 Detailed Analysis and Results

The data reported in Section 3 are based on a detailed analysis of the forest management, harvesting, hauling, and manufacturing processes as surveyed and reported for Washington state. Harvested volume was allocated to specific forest types and milling types as shown in Figure 3.

4.1 Forest Management and Timber Harvesting LCA Processes

Input data from PAH were aggregated into second growth (80-year-old) stands and third growth (40-year-old) stands for the forestry analysis to more accurately represent the different impacts that occur as a function of volume, piece size, and harvest efficiency. Data on forest management operations, including required reforestation obligations, harvest operations, yield, and product allocation (pulp versus sawlog) were used to generate a forest resource LCA which serves as the upstream process for wood product manufacturing. As 55% of the harvest volume came from the second growth harvest, 55% of the impacts associated with second growth harvesting were attributed to the average roundwood input for milling with the remainder coming from the third growth harvest (Figure 3).

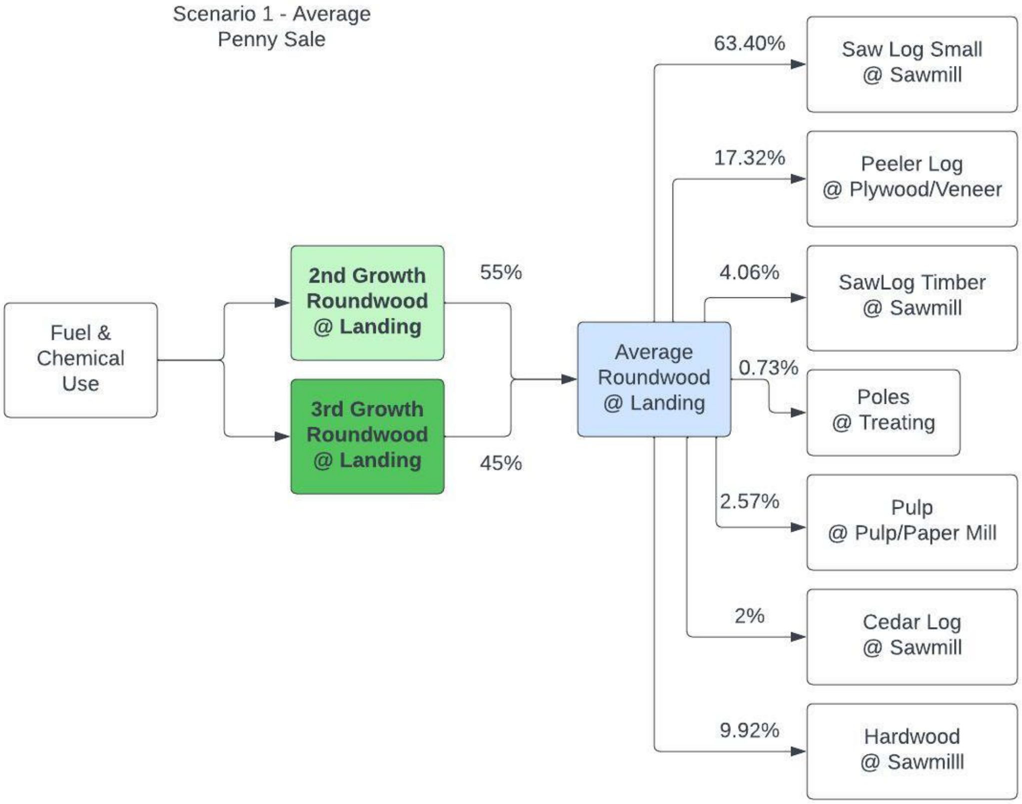

Figure 3: Forestry (A1), Hauling (A2) and Manufacturing (A3) allocations for PAH

Background data from the most recent published forest management LCA for the PNW (Oneil and Puettmann 2017) were used as secondary inputs to augment provided harvest and hauling data. PAH case study data show that harvesting 80-year-old second growth can be done with 11% fewer emissions from harvesting than if wood is sourced from third growth (40-year-old stands). This is purely a function of piece size and volume which determine logging efficiency. The more dramatic comparison arises when we look at our most competitive US region – the US Southeast. Logs delivered to mills in the PNW from our 80-year-old DNR stands carry a 40% lower environmental footprint to those from the SE. When 40-year-old second growth is harvested the emission differential is about 5%.

When trees are harvested about 1/3 to 1/2 the biomass (tops, branches, stumps, roots) associated with the harvested trees are left in the forest. These forest residues are either piled and burned or left to decay in situ. As the DNR piles debris, but does not burn it, only impacts associated with piling, but not burning were incorporated into the forest resources LCA. Decay was tracked as part of the mass balance in Table 2. At each stage in processing, carbon is tracked along with the products and coproducts as they move through the system. Details of the carbon consequences of each milling type for the major products are shown in section 4.2 through 4.9.

4.2 Softwood Lumber – Explanation of Results

Results presenting the carbon impact of producing softwood lumber (construction lumber and large timbers) using a weighted average harvest volume from the Penny Alderwood Harvest (PAH) are in Table 4 Carbon results for softwood lumber production from logs destined for construction lumber and large timber facilities from using the Penny Alderwood Harvest (PAH). Results are presented for single units one cubic meter (m3) and one square meter (m2) for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of logs from the PAH destined construction lumber and large timber facilities. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison, Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for softwood lumber.

> Column 1 is the variable description.
>
> Column 2 is the unit used for column 3 and 4
>
> Column 3 is the values for each variable in column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison.
>
> Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for softwood lumber.

4.3 Explanation of Table 4

1. Log input, m3
    a. It takes 1.20 cubic meters of log to produce 1 cubic meter of softwood lumber. The 0.20 cubic meters would equate to the biofuel used internally to dry to the lumber
    b. There were approximately 22,245 cubic meters of logs harvested that were sent to facilities that produced construction lumber including large timbers
2. Softwood Lumber
    a. Column 3 = production of 1 cubic meters
    b. Column 4 equates to the production of softwood construction lumber that was produced including large timbers from the Penny Alderwood Harvest
    c. Product mass, kg – uses the density of the wood, in this case we used a western species average density of 490 kg/m3 (oven dry), to convert wood volume to a mass. We do this to calculate the carbon content of wood.
    d. Column 4 equates to the total mass of softwood lumber (construction lumber and large timbers) harvested from the Penny Alderwood Harvest.
3. Embodied carbon - The embodied carbon is the global warming impact or all the greenhouse gas emissions through production of the product. Referred to as the global warming potential (GWP) based on the results from an accepted impact method e.g., TRACI. Embodied carbon does not include the carbon stored in the product. Embodied carbon does not include the CO2

released from biogenic sources, e.g., wood combustion. Embodied carbon does include other releases from biogenic sources, e.g., methane from wood combustion

   a. For 1 cubic meter of lumber, the embodied carbon (GWP) was 59.10 kg of CO2e, cradle to gate.
   b. For the total amount of softwood lumber volume produced from the PAH (22,245 m3), this equates to a total carbon emission of 1,097,496 kg CO2e.

4. Carbon storage in wood measured in CO2– Carbon dioxide isn't stored in wood; carbon is stored in wood. If that carbon were released into the atmosphere, it would combine with oxygen to form carbon dioxide. Carbon has a molecular weight of 12. Oxygen has a molecular weight of 16. Carbon dioxide has one carbon and two oxygens for a molecular weight of 44. For every 12 lbs of carbon stored in wood, there is an equivalent of 44 pounds of carbon dioxide that would otherwise occur the atmosphere. We assume a carbon content of wood to be 50% of oven dry wood.
   a. For 1 cubic meter of lumber the carbon stored is = 490 kg*0.5*(44/12) = 898.33 kg CO2e
   b. Scaling this to the amount of lumber produced from the PAH = 16.68 million kg CO2e
5. Net Carbon emission – this is the difference between carbon stored and carbon released (embodied carbon)
   a. For 1 cubic meter of lumber = -893.23 kg of CO2, ***more carbon is stored then released from cradle to gate***
   b. Scaling this to the amount of lumber produced from the PAH = - 15.58 million kg of CO2e
6. Substitution - .This analysis provides estimated information on the emissions of wood products versus an equivalent alternative building material. How much carbon does the product store, what is the embodied carbon, what is the displacement between the two or the avoided emission.
   a. For softwood lumber, a square meter of wall was used for the equivalent functional unit for comparing steel with wood framing.
   b. There is 10.29 kg of wood in a square meter of wall. We can equate this to harvest which is estimated at 884,280 million square meters of wall could be built from the PAH. 9,099,240 kg/PAH divided by 10.29 kg/m2 wall = 884,280 m2/PAH
   c. There is 4.15 kg/m2 of steel studs in a wall. Equating this to the PAH, there is 884,280 m2 of wall that can be constructed from the PAH multiplied by 4.15 m2/wall = 3.67 million m2.
   d. Embodied carbon for 1 meter square of wood wall = 1.05 kg CO2e and 1.2 million kg CO2e for the square meter of wall from the PAH. 1.05 kg CO2e/m2x 884,280 m2
   e. Embodied carbon for 1 meter square of steel wall = 17.97 kg of CO2e and 15.89 million kg CO2e for PAH. Again, this is multiplication of the total square meter equivalent from the harvest of PAH.
   f. Carbon stored in a square meter of wood wall = 18.87 kg CO2e and 16.68 million kg CO2e from the PAH.
   g. Avoided emission by using a wood wall versus a steel wall = 16.92 kg CO2e/m2 and 14.96 million kg CO2e/PAH (softwood lumber only). This number does not consider carbon storage. These values are calculated by taking the absolute difference between the embodied carbon of wood and steel.

Table 4 Carbon results for softwood lumber production from logs destined for construction lumber and large timber facilities from using the Penny Alderwood Harvest (PAH). Results are presented for single units one cubic meter (m3) and one square meter (m2) for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of logs from the PAH destined construction lumber and large timber facilities. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison, Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for softwood lumber.

1	2	3	4
		per m3 of product	**PAH**
Softwood Lumber			
Log input, m3 – allocated to lumber		1.20	22,245
		per m3 of product	**PAH**
Softwood Lumber			
Production	m3	1.00	18,570
Product mass	kg	490.00	9,099,240
Embodied carbon	kg CO2e	59.10	1,097,496
Carbon storage	kg CO2e	898.33	16,681,941
Net - carbon emissions	kg CO2e	(839.23)	(15,584,444)
SUBSTITUTION		**per m2 of wall**	**m2 equivalent to PAH**
Wall	m2	1	**884,280**
Wood stud walls, mass	kg	10.29	9,099,240
Steel studs wall, mass	kg	4.15	3,669,762
Embodied carbon, Wood stud wall	kg CO2e	1.05	932,031
Embodied carbon, Steel stud wall	kg CO2e	17.97	15,890,510
Carbon storage, wood wall	kg CO2e	18.87	16,681,941
Carbon storage, steel wall	kg CO2e	0	0
Avoided emission by using wood stud over a steel stud	kg CO2e	16.92	14,958,479.15

4.4 Softwood Plywood – Explanation of Results

Results presenting the carbon impact of producing softwood plywood using a weighted average harvest volume from the PAH are in Table 5 Carbon results for softwood plywood production from logs destined for veneer or plywood facilities from the Penny Alderwood Harvest (PAH). Results are presented for single units one cubic meter (m3) and one square meter (m2) for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of peeler logs from the PAH. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in Column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison, Column 4 attempts to equate the variables in Column 1 scaled to what was harvested from the PAH for veneer or plywood.

Column 1 is the variable description.

Column 2 is the unit used for column 3 and 4

Column 3 is the values for each variable in column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison.

Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for a veneer log.

4.5 Explanation of Table 5

7. Log input, m3
    a. It takes 1.39 cubic meters of log to produce 1 cubic meter of softwood plywood. The 0.39 cubic meters would equate to the biofuel used internally for energy to condition, dry, and press veneer and plywood.
    b. There were approximately 6,720 cubic meters of logs harvested that were sent to facilities that produced softwood plywood.
8. Softwood plywood
    a. Column 3 = production of 1 cubic meters
    b. Column 4 equates to the production of softwood construction lumber that was produced including large timbers from the PAH, 4,818 cubic meters
    c. Product mass, kg – uses the density of the wood, in this case we used a western species average density of 458 kg/m3 (oven dry), to convert wood volume to a mass. We do this to calculate the carbon content of wood.
    d. Column 4 equates to the total mass of softwood lumber (construction lumber and large timbers) harvested from the PAH, 2.2 million kg.
9. Embodied carbon - The embodied carbon is the global warming impact or all the greenhouse gas emissions through production of the product. Referred to as the global warming potential (GWP) based on the results from an accepted impact method e.g., TRACI. Embodied carbon does not include the carbon stored in the product. Embodied carbon does not include the CO2 released from biogenic sources, e.g., wood combustion. Embodied carbon does include other releases from biogenic sources, e.g., methane from wood combustion
    a. For 1 cubic meter of plywood the embodied carbon (GWP) was 110.45 kg CO2e, cradle to gate.
    b. For the total amount of softwood plywood volume produced from the PAH (4,818 m3), this equates to a total carbon emission of 532,162 kg CO2e.
10. Carbon storage in wood measured in CO2– Carbon dioxide is not stored in wood; carbon is stored in wood. If that carbon were released into the atmosphere, it would combine with oxygen to form carbon dioxide. Carbon has a molecular weight of 12. Oxygen has a molecular with of 16. Carbon dioxide has one carbon and two oxygens for a molecular weight of 44. For every 12 lbs of carbon stored in wood, there is an equivalent of 44 pounds of carbon dioxide that would otherwise occur the atmosphere. We assume a carbon content of wood to be 50% of oven dry wood.
    a. For 1 cubic meter of plywood the carbon stored is = 458 kg*0.5*(44/12) = 839.67 kg CO2e
    b. Scaling this to the amount of plywood produced from the PAH = 4.05 million kg CO2e

11. Net Carbon emission – this is the difference between carbon stored and carbon released (embodied carbon)
    a. For 1 cubic meter of plywood = -729 kg of CO2, ***more carbon is stored then released from cradle to gate***
    b. Scaling this to the amount of plywood produced from the PAH = - 3.5 million kg of CO2e
12. Substitution - This analysis provides estimated information on the emissions of wood products versus an equivalent alternative building material. This is based on the embodied carbon of the unit (e.g., 1 m2 of wall). Oriented strandboard is produced primarily in Canada and the southeast and to a lesser extent in the Midwest of the United States. NOTE the transportation of the product from production locations to the Pacific Northwest is outside the scope of this study, but it would increase the embodied carbon of the OSB over locally produced plywood.
    a. For softwood plywood, a square meter of wall was used for the equivalent functional unit for comparing plywood with OSB sheathing.
    b. There is 6.11 kg of plywood in a square meter of wall. We can equate this to harvest which is estimated at 361,147 million square meters of wall sheathing could be produced from the PAH. 2,206,607 kg/PAH divided by 6.11kg/m2 wall = 361,147 m2/PAH.
    c. There is 8.13 kg/m2 of OSB sheathing in a wall. Equating this to the PAH, there is 361,147 m2 of wall that can be constructed from the PAH multiplied by 8.13 m2/wall = 2.97 million m2.
    d. Embodied carbon for 1 meter square of plywood sheathing = 2.34 kg CO2e and 845,806 kg CO2e for the square meter of wall from the PAH. 2.34 kg CO2e/m2 x 361,147 m2
    e. Embodied carbon for 1 meter square of OSB sheathing = 2.62 kg CO2e and 946,205 kg CO2e for PAH. Again, this is multiplication of the total square meter equivalent from the harvest of PAH.
    f. Carbon stored in a square meter of Plywood sheathing = 11.20 kg CO2e and 4.01 million kg CO2e from the PAH.
    g. Carbon stored in a square meter of OSB sheathing = 14.90 kg CO2e and 5.38 million kg CO2e from the PAH.
    h. Avoided emission by using a plywood sheathing in a wall versus a OSB sheathing = 0.28 kg CO2e/m2 and 100,399 kg CO2e/PAH (veneer logs only). This number does not consider carbon storage. These values are calculated by taking the absolute difference between the embodied carbon of plywood and OSB.

Table 5 Carbon results for softwood plywood production from logs destined for veneer or plywood facilities from the Penny Alderwood Harvest (PAH). Results are presented for single units one cubic meter (m3) and one square meter (m2) for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of peeler logs from the PAH. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in Column 1 per cubic meter of product or square meter of wall (equivalent functional units) for the substitution comparison, Column 4 attempts to equate the variables in Column 1 scaled to what was harvested from the PAH for veneer or plywood.

1	2	3	4
		per m3 of product	**PAH**
Softwood Plywood			
Log input, m3		1.39	6,720
		per m3 of product	**PAH**
Softwood Plywood			
Production	m3	1.00	4,818
Product mass	kg	458.00	2,206,607
Embodied carbon	kg CO2e	110.45	532,162
Carbon storage	kg CO2e	839.67	4,045,446
Net - carbon emissions	kg CO2e	(729.21)	(3,513,284)
SUBSTITUTION		**per m2 of wall**	**m2 equivalent to PAH**
Wall	m2	1	**1,173,992**
Plywood, mass	kg	6.11	2,206,607
OSB, mass	kg	8.13	2,934,679
Embodied carbon, plywood wall,	kg CO2e	2.34	845,806
Embodied carbon, OSB wall	kg CO2e	2.62	946,205
Carbon storage, plywood wall	kg CO2	11.20	4,045,446
Carbon storage, OSB wall	kg CO2	14.90	5,380,245
Avoided emission by using plywood over OSB sheathing	kg CO2e	0.28	100,399

4.6 Poles – Explanation of Results

Results presenting the carbon impact of producing softwood utility poles using a weighted average harvest volume from the PAH are in Table 6.

Column 1 is the variable description.

Column 2 is the unit used for column 3 and 4

Column 3 is the values for each variable in column 1 per cubic meter of product or one utility pole (equivalent functional units) for the substitution comparison.

Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for a pole log.

4.7 Explanation of Table 6

13. Log input, m3
    a. It takes 1.0 cubic meters of log to produce 1 cubic meter of pole.
    b. There were approximately 343 cubic meters of logs harvested that were sent to facilities that produce poles.
14. Poles
    a. Column 3 = production of 1 cubic meters
    b. Column 4 equates to the production of poles that was produced from the PAH, 343 cubic meters
    c. Product mass, kg – uses the density of the wood, in this case we used a western species average density of 490 kg/m3 (oven dry), to convert wood volume to a mass. We do this to calculate the carbon content of wood.
    d. Column 4 equates to the total mass of poles harvested from the PAH, 167,850 kg.
15. Embodied carbon - The embodied carbon is the global warming impact or all the greenhouse gas emissions through production of the product. Referred to as the global warming potential (GWP) based on the results from an accepted impact method e.g., TRACI. Embodied carbon <u>does not include</u> the carbon stored in the product. Embodied carbon <u>does not include</u> the CO2 released from biogenic sources, e.g., wood combustion. Embodied carbon <u>does include</u> other releases from biogenic sources, e.g., methane from wood combustion
    a. For 1 cubic meter of an untreated pole the embodied carbon (GWP) was 14.64 kg CO2e, cradle to gate. For PAH = 5,015 kg CO2e
    b. For 1 cubic meter of a treated pole the embodied carbon (GWP) was 346 kg CO2e, cradle to gate. For PAH = 118,335 = 346 kg/m3 x 343 m3.
16. Carbon storage in wood measured in CO2– Carbon dioxide is not stored in wood; carbon is stored in wood. If that carbon were released into the atmosphere, it would combine with oxygen to form carbon dioxide. Carbon has a molecular weight of 12. Oxygen has a molecular with of 16. Carbon dioxide has one carbon and two oxygens for a molecular weight of 44. For every 12 lbs of carbon stored in wood, there is an equivalent of 44 pounds of carbon dioxide that would otherwise occur the atmosphere. We assume a carbon content of wood to be 50% of oven dry wood.
    a. For 1 cubic meter of pole (treated or untreated) the carbon stored is = 490 kg*0.5*(44/12) = 898.33 kg CO2e
    b. Scaling this to the volume of poles produced from the PAH = 307,724 kg CO2e
17. Net Carbon emission – this is the difference between carbon stored and carbon released (embodied carbon)
    a. For 1 cubic meter of pole = -553 kg of CO2e, ***more carbon is stored then released from cradle to gate***
    b. Scaling this to the volume of poles produced from the PAH = - 189,389 kg of CO2e
18. Substitution - This analysis provides estimated information on the emissions of wood products versus an equivalent alternative material. This is based on the embodied carbon of the unit (e.g., 1 pole). The equivalent pole comparison is presented for steel and concrete.
    a. One class 4 pole contains 0.66 m3 of wood. We can equate this to the poles harvested from PAH = 519 poles.
    b. A wood pole contains 323 kg. Equating this to the PAH, 519 poles weigh 167,850 kg.
    c. Embodied carbon for 1 treated pole = 228 kg CO2e and 188,335 kg CO2e poles from the PAH.

d. Embodied carbon for 1 steel pole = 3,190 kg CO2e and 1,699 kg CO2e for a concrete pole. For PAH these values were multiplied by the number of poles harvested which is 1.66 and 0.88 million kg CO2e for steel and concrete, respectively.
e. Average embodied carbon for steel and concrete poles are 2,445 kg CO2e/pole and 1.27 million kg CO2e for PAH.
f. Carbon stored in a square meter of Plywood sheathing = 11.20 kg CO2e and 4.01 million kg CO2e from the PAH.
g. Carbon stored in one pole = 593 kg CO2e and 307,724 kg CO2e from the PAH. No carbon is stored in the steel or concrete poles.
h. Avoided emission by using a wood poles versus an average of a steel and concrete pole are 2,217 kg CO2e/m2 and over 1.15 million kg CO2e/PAH (pole logs only). This number does not consider carbon storage. These values are calculated by taking the absolute difference between the embodied carbon of wood pole and the average embodied carbon of steel and concrete.

Table 6 Carbon results for pole production from logs destined for pole facilities from the Penny Alderwood Harvest (PAH). Results are presented for single units one cubic meter (m3) and one pole for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of pole logs from the PAH. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in Column 1 per cubic meter of product or 1 pole (equivalent functional units) for the substitution comparison, Column 4 attempts to equate the variables in Column 1 scaled to what was harvested from the PAH for poles.

1	**2**	**3**	**4**
		per m3 of product	**PAH**
Poles			
Log input, m3		1.00	343
		per m3 of product	**PAH**
Poles			
Production, untreated	m3	1.00	343
Product mass, untreated	kg	490.00	167,850
Embodied carbon, untreated	kg CO2e	14.64	5,015
Embodied carbon, treated	kg CO2e	345.45	118,335
Carbon storage	kg CO2	898.33	307,724
Net - Carbon emissions - treated	kg CO2e	(552.88)	(189,389)
SUBSTITUTION		**per m2 of wall**	**m2 equivalent to PAH**
Poles	qty	1.00	519
Mass of pole(s), untreated	kg	323.40	167,850
Embodied carbon, penta treated	kg CO2e	228.00	118,335
Embodied carbon, galv. Steel	kg CO2e	3,190.00	1,655,658
Embodied carbon, concrete	kg CO2e	1,699.00	881,807
Embodied carbon, steel + concrete average	kg CO2e	2,444.50	1,268,733
Carbon storage in wood pole	kg CO2e	592.90	307,724
Carbon storage in steel pole	kg CO2e	-	-
Carbon storage in concrete pole	kg CO2e	-	-
Net - carbon emissions steel	kg CO2e	(2,962.00)	(1,537,323)
Net - carbon emissions concrete	kg CO2e	(1,471.00)	(763,4713)
Net - carbon emissions average	kg CO2e	(2,216.50)	(1,150,397)
Avoided emission by using Wood pole over average steel and concrete pole	kg CO2e	2,216.50	1,150,397

4.8 Hardwood Lumber – Explanation of Results

Results presenting the carbon impact of producing hardwood lumber using a weighted average harvest volume from the PAH are in Table 7.

Column 1 is the variable description.

Column 2 is the unit used for column 3 and 4

Column 3 is the values for each variable in column 1 per cubic meter of product or one cabinet front (equivalent functional units) for the substitution comparison.

Column 4 attempts to equate the variables in column 1 scaled to what was harvested from the PAH for a hardwood logs.

4.9 Explanation of Table 7

19. Log input, m3
    a. It takes 4.52 cubic meters of log to produce 1 cubic meter of hardwood lumber, this includes 74% coproduct.
    b. This equates to approximately 843 cubic meters of logs required produce hardwood lumber.
20. Hardwood Lumber
    a. Column 3 = production of 1 cubic meters
    b. Column 4 equates to the production of hardwood lumber that was produced from the PAH; 186 cubic meters harvested
    c. Product mass, kg – uses the density of the wood, in this case we used an average density of 420 kg/m3 (oven dry), to convert wood volume to a mass. We do this to calculate the carbon content of wood.
    d. Column 4 equates to the total mass of hardwood lumber harvested from the PAH, 78,288 kg.
21. Embodied carbon - The embodied carbon is the global warming impact or all the greenhouse gas emissions through production of the product. Referred to as the global warming potential (GWP) based on the results from an accepted impact method e.g., TRACI. Embodied carbon does not include the carbon stored in the product. Embodied carbon does not include the CO2 released from biogenic sources, e.g., wood combustion. Embodied carbon does include other releases from biogenic sources, e.g., methane from wood combustion
    a. For 1 cubic meter of hardwood lumber the embodied carbon (GWP) was 17.94 kg CO2e, cradle to gate. For PAH = 3,343 kg CO2e
22. Carbon storage in wood measured in CO2e– Carbon dioxide is not stored in wood; carbon is stored in wood. If that carbon were released into the atmosphere, it would combine with oxygen to form carbon dioxide. Carbon has a molecular weight of 12. Oxygen has a molecular with of 16. Carbon dioxide has one carbon and two oxygens for a molecular weight of 44. For every 12 lbs of carbon stored in wood, there is an equivalent of 44 pounds of carbon dioxide that would otherwise occur the atmosphere. We assume a carbon content of wood to be 50% of oven dry wood.
    a. For 1 cubic meter of hardwood lumber the carbon stored is = 420 kg*0.5*(44/12) = 770 kg CO2e

    b. Scaling this to the volume of hardwood lumber produced from the PAH = 143,529 kg CO2e

23. Net Carbon emission – this is the difference between carbon stored and carbon released (embodied carbon)
    a. For 1 cubic meter of hardwood lumber = -752 kg of CO2e, ***more carbon is stored then released from cradle to gate***
    b. Scaling this to the volume of hardwood lumber produced from the PAH = - 140,185 kg of CO2e
24. Substitution - This analysis provides estimated information on the emissions of wood products versus an equivalent alternative material. This is based on the embodied carbon of the unit (e.g., one cabinet door). The equivalent cabinet door is compared for medium density fiberboard (MDF).
    a. In order to produce 1 hardwood cabinet door, it requires 4.88 kg of hardwood lumber (CINTRAFOR 2022). For the PAH, this equates to 16,030 cabinet doors weighing in at 78,288 kg based on the harvest of hardwood logs (assuming all go to cabinets).
    b. The same size MDF cabinet door requires 7.27 kg of an MDF panel. For the PAH, this equates to 91,104 cabinet doors
    c. Embodied carbon for producing 1 hardwood cabinet door = 0.420 kg CO2e and 6,733 kg CO2e from the PAH.
    d. Embodied carbon for 1 MDF cabinet door = 0.75 kg CO2e and 68,328 for PAH
    e. The mass of a solid cabinet door is 4.88 kg per door. The carbon stored in a wood cabinet door= 8.95 kg CO2e and 143,529 kg CO2e from the PAH.
    f. The mass of an MDF cabinet door is 7.27 kg per door. The carbon stored in a MDF cabinet door= 1,214,129 kg CO2e from the PAH.
    g. Avoided emission by using a wood cabinet door over an MDF door is 0.33 kg CO2e/m2 and 61,595 kg CO2e/PAH. This number does not consider carbon storage. These values are calculated by taking the absolute difference between the embodied carbon of wood cabinet door and the embodied carbon of an MDF door.

Table 7 Carbon results for cabinet door production from logs destined for hardwood manufacturing facilities from the Penny Alderwood Harvest (PAH). Results are presented for single units one cabinet door and one MDF wood cabinet door for the substitution impacts. Results are also presented by equating the production, carbon storage, embodied carbon, and substitution impacts based on the harvest of hardwood sawlogs from the PAH. Column 1 is the variable description, Column 2 is the unit used for column 3 and 4, Column 3 is the values for each variable in Column 1 per cubic meter of product or per equivalent functional unit for the substitution comparison, Column 4 attempts to equate the variables in Column 1 scaled to what was harvested from the PAH for hardwood lumber.

1	2	3	4
		per m3 of product	**PAH**
Hardwood Lumber, allocated to lumber			
Log input, m3		4.52	843
		per m3 of product	**Penny Alderwood Harvest**
Hardwood Lumber			
Production	m3	1.00	186
Product mass	kg	420.00	78,288
Embodied carbon	kg CO2e	17.94	3,343
Carbon storage	kg CO2e	770.00	143,529
Net - carbon emissions	kg CO2e	(752.06)	(140,185)
SUBSTITUTION		**per Cabinet Door**	**per equivalent to PA harvest**
Solid wood Cabinet door(s)	qty	1	16,030
MDF wood Cabinet door(s)	qty	1	91,104
Hardwood dried sanded, input material	kg	4.88	78,288
MDF finish, wood only, input material	kg	7.27	662,252
Embodied carbon, hardwood	kg CO2e	0.420	6,733
Embodied carbon, MDF	kg CO2e	0.75	68,328
Carbon storage, hardwood, 1 door	kg CO2e	8.95	143,529
Carbon storage, MDF, 1 door	kg CO2e	13.33	1,214,129
Net - carbon emissions hardwood	kg CO2e	(8.53)	(136,796)
Net - carbon emissions MDF	kg CO2e	(12.58)	(1,145,801)
Avoided emission by using hardwood lumber over MDF	kg CO2e	0.33	61,595.32

5 Conclusions

Based on the data supplied for the PAH, known harvesting, hauling, milling, and substitution emissions, plus forest growth and residue decay estimates, it appears that leaving an 80-year old forests for carbon storage may not be the best carbon storage alternative. Caveats to that conclusion are driven by variations in the forest inventory, milling capacity, and likely substitutions.

On the forestry side of the equation, if the 80-year old stand had higher stocking than PAH with definite indications of the potential for additional growth, leaving older forests may provide a positive carbon benefit to the atmosphere. However, it is unlikely to sustain a positive trend over the long term based on FIA data on older forest stand dynamics which show a clear decline in growth rate after 70 years in the PNW for almost all species. As site carrying capacity is a limiting factor for maximum carbon accumulation, modern forest management practices may reach that decline in growth rate much earlier than 70 years as has been quantified in the US South for intensively managed plantations (Oneil, 2021a).

We deliberately analyzed a conservative suite of substitute products to provide a generalized estimate of the outcome of harvest versus no-harvest alternatives. If the substitutions were for petrochemical products (e.g., plastic and metal doors and gypsum board instead of alternative wood products), or for uses such as in cross laminated timber, leaving the 80-year old stand unharvested would look much worse than this case study suggests.

Overall, this analysis provides a somewhat conservative estimate of the carbon costs and benefits of harvesting these older stands, especially if they are in decline and are not fully stocked. It also directly addresses the limitations of the discussion surrounding carbon debt from timber harvests.

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7 Appendix A: The Penny Alderwood Timber Sale data

Penny Alderwood Timber Sale Cutout information									
	DNR Net Acres : 246 Acres								
		Net Volume MBF							
Sawlog Destinations	**Location**	**WH**	**DF**	**WRC**	**Red Alder**	**Maple**	**TOTAL MBF**	**Total Tons Sawlogs**	**Average Tons/MBF**
Dahlstrom Lumber Co	Hoquiam	0.4	21.2				21.6	100.656	4.66
BuseTimber	Everett		107.26				107.26	480.5248	4.48
Canyon Lumber	Everett		199.13				199.13	912.0154	4.58
Port Angeles Hardwoods	Port Angeles			2.75	161.53	34.41	198.69	1611.3759	8.11
Murphy Veneer	Elma		1167.38		23.08		1190.46	6368.961	5.35
Stella-Jones	Rochester		43.51				43.51	268.4567	6.17
Sierra Pacific Industries	Aberdeen	181.18	367.3	1.36		0.19	550.03	3212.1752	5.84
Sierra Pacific Industries	Shelton	518.71	1998.1				2516.81	20159.6481	8.01
Alta Forest Products	Shelton			114.45			114.45	732.48	6.4
Northwest Hardwoods	Centralia				281.56	5.47	287.03	2049.3942	7.14
	TOTAL	**700.29**	**3903.88**	**118.56**	**466.17**	**40.07**	**5228.97**	**35895.6873**	**6.8647721**
DNR Volume Estimate from Prospectus		851	3388	131	556	150	5076		
Pulp log Destinations	**Location**	**Conifer Tons**	**Hardwoods Tons**	**Total Tons Pulp Logs**	**Avg Tons/Load**				
Port Townsend Paper	Port Angeles	658.76		658.76	15.32				
Port Angeles Hardwoods	Port Angeles		285.6	285.6	16.8				
	TOTAL	658.76	285.6	944.36	15.74				
All shovel logging									

8 Appendix B: Forest Inventory and Analysis Forest Carbon by Inventory Age and Species – Western Washington Species

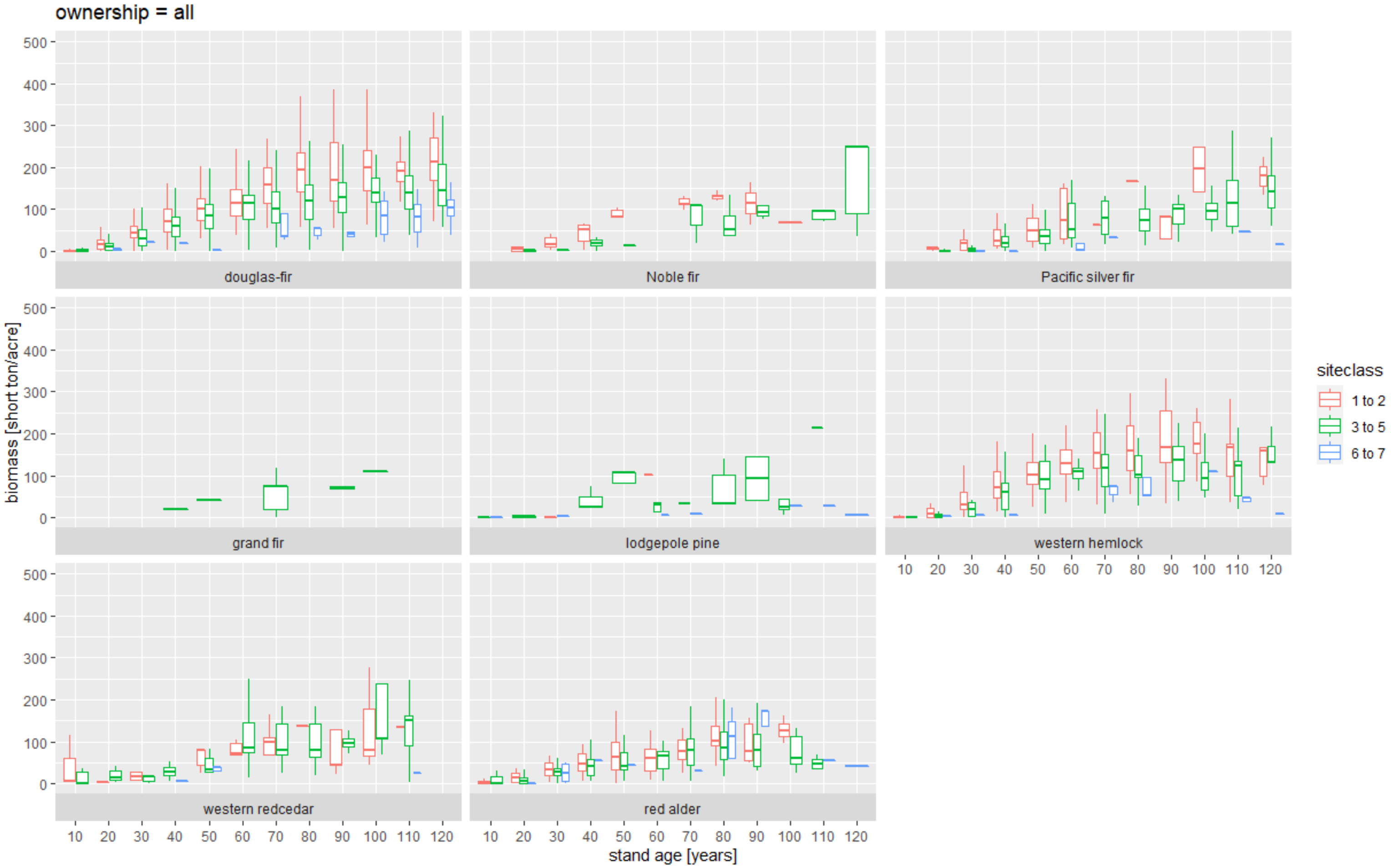

Figure 4 Biomass (average and distribution) in oven-dry short tons per acre by site class, forest type, and age for western Washington species.

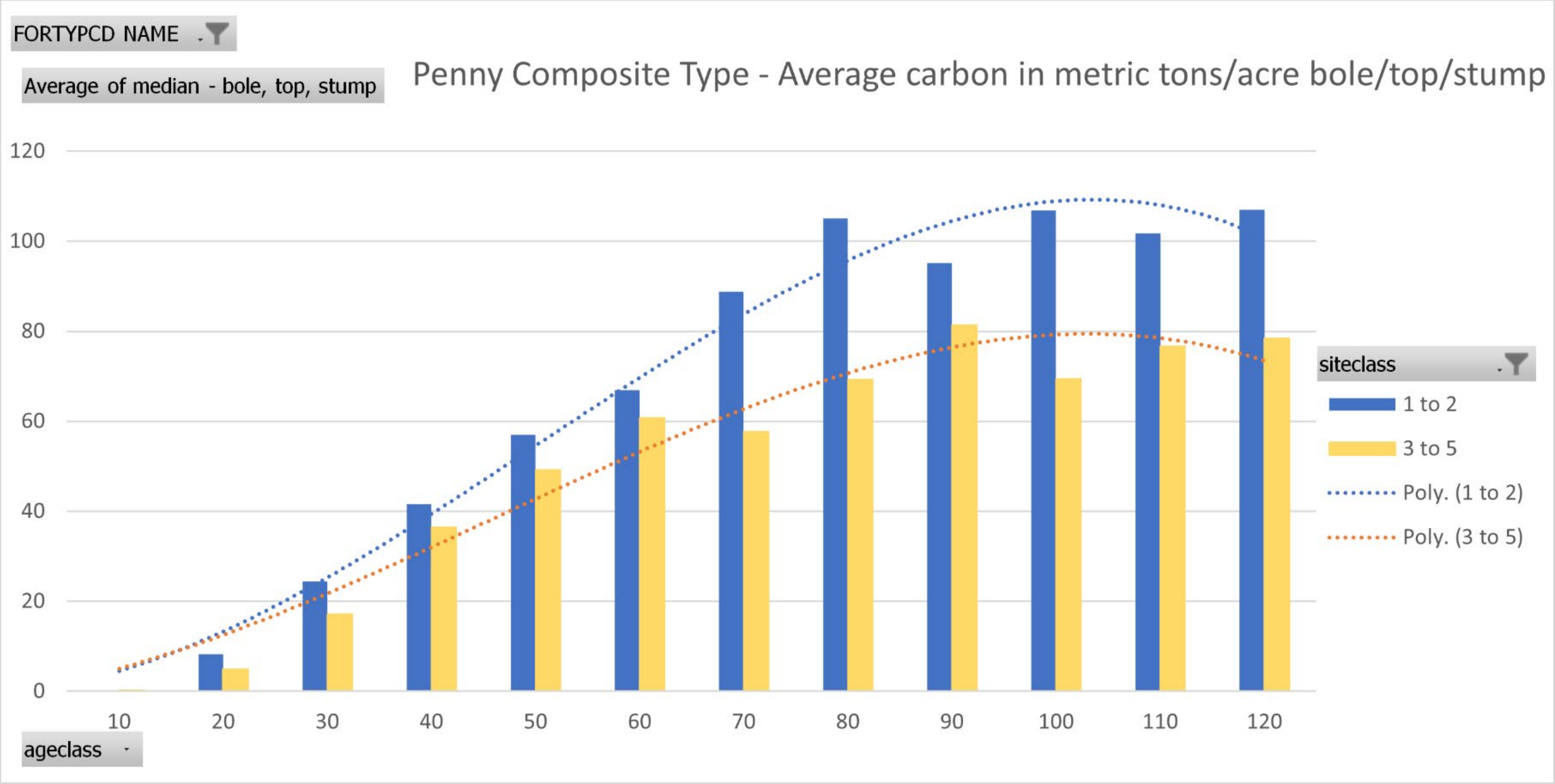

Figure 5 Average tree carbon (Mt/acre) by site class for Penny Sale species mix by age class, excluding roots.

Average above ground tree carbon for the two site classes with this species mix from age 80-120 is 89.1 plus an estimated 16.5 MT/acre of roots.

Bole biomass for PAH 80-year-old stand is 68 MT/acre. Using component ratio allocations, the estimated total tree biomass per acre is 99.14 MT/ac. As the stand contains a deciduous component, its growth increment is marginal between 80-120 years based on FIA estimates (Table 8 – see highlighted portions).

Table 8: FIA estimates of average metric tons/acre of mixed species forest inventory by age and site class.

Penny Composite Species mix (DF, RA, WH, RC)			
Average carbon in metric tons/acre for AGB = bole, top, stump			
	Site Class Group		
Age Class	1 to 2	3 to 5	Average of site classes
10	0.2	0.0	0.1
20	8.3	4.9	6.6
30	24.4	17.1	20.8
40	41.5	36.4	39.0
50	56.9	49.1	53.0
60	66.9	60.7	63.8
70	88.8	57.7	73.2
80	105.1	69.3	87.2
90	95.2	81.4	88.3
100	106.8	69.4	88.1
110	101.8	76.6	89.2
120	107.0	78.4	92.7

9 Appendix C: UW Forest Carbon Modeling Framework

To facilitate comparison between alternatives, data from the forest carbon modeling framework recently released by the University of Washington (Ganguly et al. 2023) showing carbon allocations of current growth by landowner category were adapted to inputs from the PAH for comparability to current DNR harvesting strategies. Models used to develop Figure 6 provide the allocation to products for the sale, but do not expand the system boundary for comparative analyses purposes. While they provide accurate estimates for the allocation of primary products, they do not calculate substitution benefits on a product by product basis as was completed herein for the primary products generated from manufacturing the logs in the PAH.

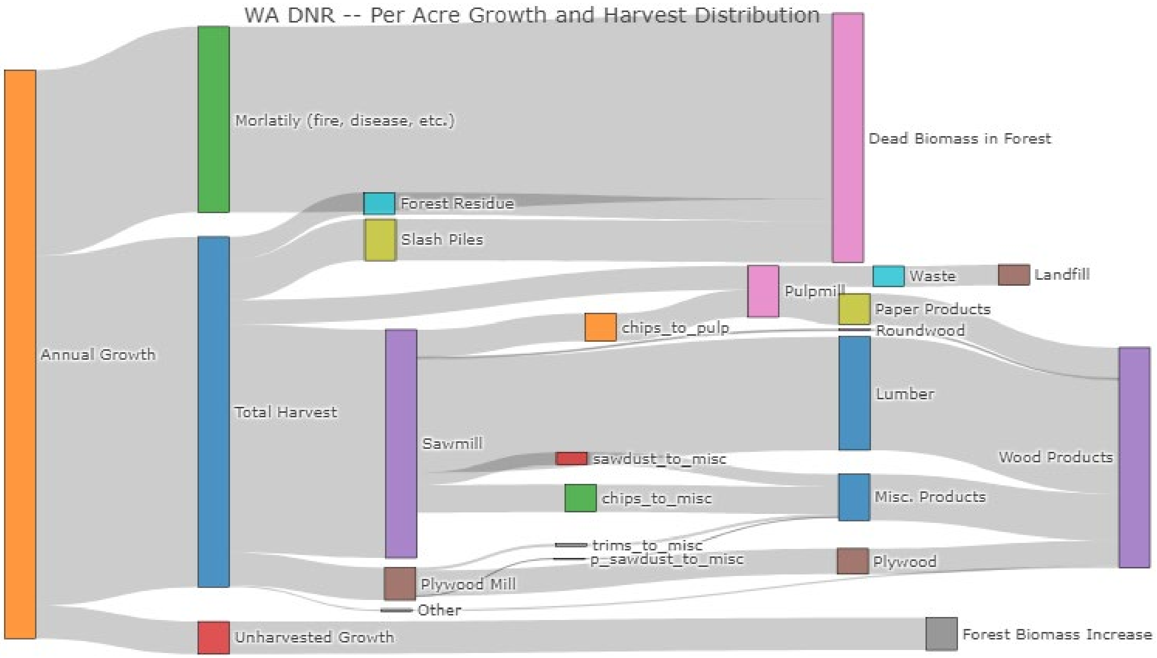

Figure 6: Per Acre Carbon Sequestration Allocation to Products, Mortality and Growth for WA DNR lands (Ganguly et al. 2023)