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ASSESSING THE REGIONAL END-OF-LIFE IMPACTS OF WOOD WASTE IN THE UNITED STATES

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ABSTRACT: The environmental impacts associated with the end-of-life (EOL) phase of construction and demolition (C&D) wood has been relatively understudied compared to earlier life cycle phases. The uncertainty associated with modeling the EOL phase of C&D products with long functional lifespans has been cited as a barrier to widespread adoption of EOL modeling in life cycle assessment studies. As such, limited studies exist for C&D wood waste treatment. In this study, four end-of-life scenarios for wood waste (recycling, composting, incinerating, and landfilling) were evaluated on a national level across the United States (U.S.), with the objectives of determining waste distribution to each scenario, scenario-specific waste transportation distances, and estimating environmental impacts, carbon storage benefits, and substitution benefits associated with each scenario. Summing the environmental impacts with the carbon storage and substitution benefits revealed a clear climate benefit for the recycling scenario in most impact categories. Moreover, when waste was diverted from the landfill scenario and recycled instead, the net environmental impacts were reduced in all impact categories. This research has improved the understanding of how differing wood waste practices across the U.S. produce different environmental impacts, which highlights areas for improvement in terms of climate and waste reduction goals.

KEYWORDS: life cycle assessment, end-of-life, wood waste, circular economy, climate change

1 – INTRODUCTION

The construction and buildings sectors have substantial contributions (37%) to annual global carbon dioxide (CO_2) emissions, with construction materials making up 11% of global emissions [1]. Global greenhouse gas emission reductions can thus be accomplished on a major scale by replacing conventional mineral-based materials with materials containing lower embodied energy, such as harvested wood products (HWP). HWP have been commonly used in construction for centuries [2], both as solid sawn products (e.g., dimensional lumber) and engineered wood products (e.g., medium-density fiberboard, particleboard, etc.). This long timeframe has enabled a comprehensive understanding of the mechanical and physical properties of HWP, which in turn has prompted technological improvements in engineered wood products [3]. This has allowed engineered wood products such as mass timber panels to replace mineral-based materials in mid-to-high-rise buildings in recent decades [4].

In addition to a robust understanding of the structural properties of HWP, the extensive history of construction wood use has facilitated studies on the environmental impacts and benefits of HWP. For example, building with cross-laminated timber instead of reinforced concrete results in a 43% reduction in embodied greenhouse gas emissions on average [5]. The past decade has seen a large increase in the number of life cycle assessment (LCA) studies of mass timber building construction as interest in estimating the environmental impacts of mass timber and other wood products continues to grow [5].

Studies of the environmental impacts of HWP have mainly focused on the production and construction stages; less data exists for the EOL stage [6]. A literature review of mass timber LCA studies

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demonstrated that 72% of the existing 169 mass timber EOL LCA studies[4] were published in the last ten years, highlighting an increasing interest in capturing the environmental burdens of waste management for wood products [7]. However, EOL studies make up less than 2% of the existing mass timber LCA literature body, which is comprised of 12,488 studies [7].

Existing literature for EOL LCAs of other wood products is also scarce, with studies citing the uncertainty associated with the long lifespans of buildings as a barrier to incorporating the EOL stage in construction LCA studies [8]. Despite this barrier, an Australian study evaluated three EOL scenarios for engineered wood products: recycle, incinerate, and landfill [9]. This study demonstrated that the preferred EOL scenario varies among environmental impact categories, but the recycle scenario is preferable for more impact categories than the other scenarios are. Moreover, the EOL stage produces fewer environmental impacts than the production stage does. However, similar research has not been conducted for engineered wood products in the U.S., or for solid sawn products. To fill this gap, this research focused on estimating the environmental impacts of waste treatment of C&D wood in the U.S., including both engineered wood products and solid sawn products. Sandin et al. [10] argue that the uncertainties inherent in EOL modeling necessitate including a variety of "functionally different" EOL scenarios to capture the influence of uncertainties on LCA results. As such, this analysis assessed four EOL scenarios for the C&D wood waste stream: recycle, compost, incinerate, and landfill.

2 – BACKGROUND

This analysis used LCA principles in accordance with the International Organization for Standardization (ISO) 14040 [11] and ISO 10444 [12]. LCA is an internationally-recognized analytical tool used to assess the environmental impacts associated with a product across its entire lifecycle. The functional unit is one metric ton of C&D wood waste. The environmental impacts for five impact categories were evaluated using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), including global warming potential (GWP_{100}), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and smog formation potential (SFP). This analysis was done for three stages of the EOL portion of the product life cycle: waste transportation, waste processing, and waste disposal. Burdens and substitution benefits produced outside the system boundary (i.e., during new product manufacturing[5]) were also assessed in this analysis, with the substitution for fossil products being applied to the system to avoid the allocation of impacts across multiple functional lifespans. This paper adopted a focus on Sustainability and Timber in a Circular Economy.

2.1 Research Objectives

The overarching goal of this research was to produce a robust assessment of the environmental impacts associated with the C&D wood waste stream in the U.S. in different EOL scenarios, including recycling into particleboard, composting, incinerating, and landfilling. This research encompassed analyses of LCA data for C&D wood waste treatment in the U.S. on a national level. This research aimed to address the following objectives:

1) Determine wood waste distribution to the four EOL scenarios on a national level.
2) Conduct logistics modeling to estimate transportation distances from waste generation sites to waste processing facilities.
3) Estimate environmental impacts, carbon storage, and substitution benefits for each EOL scenario.
4) Calculate the environmental impacts, carbon storage, and substitution benefits of disposing one metric ton of wood waste in the U.S. on a national level as a case study.

3 – BACKGROUND

3.1 Waste Distribution

Data for wood waste distribution to the EOL scenarios was compiled from statewide C&D waste characterization studies [13][14]. These studies report distribution of waste to different EOL treatments by material type and category (e.g., C&D wood waste). Some studies report distribution by mass, while others reported distribution by percentages; all distribution data were converted to percentages. If any state did not have any published waste characterization studies or if a

[4] EOL-specific studies were identified by using "end-of-life", "end of life", or "EOL" as keywords.

[5] New product manufacturing is involved for the recycle and compost scenarios, which produce particleboard and compost, respectively.

state's study did not report data for wood waste or C&D waste, the state was omitted. The national average distribution to each EOL scenario was calculated by averaging distribution rates reported by individual states.

3.2 Transportation Modeling

The "Closest Facility" tool in the "Network Analyst" toolbox of the geospatial software ArcGIS Pro v3.2 was used to estimate transportation distances between major cities and the closest three waste processing facilities for each EOL scenario. The "Closest Facility" tool identifies the closest facility to a feature, then uses a specified route network to map the transportation distance between the two points. Data were compiled on the locations of major cities [15], wood waste recyclers [16], composting facilities [17], waste incinerators [18], and C&D landfills [19], as well as freight transportation routes [20]. These data were imported into the "Closest Facility" tool using the WGS 1984 coordinate system.

The "Closest Facility" tool generates thousands of routes between cities and waste processing facilities as its output layer. This output layer is used in the "Pairwise Intersect" tool along with each region layer to create layers of routes for each region. Then, for each of these layers, the distance in kilometers for each route was calculated in the output table using the "Calculate Geometry" function. The mean distance was calculated using the Visualize Statistics function. This provides the mean transportation distance between cities and waste processing facilities in each state. This process flow was replicated separately for each EOL scenario, resulting in four mean transportation distances for recycling, composting, incinerating, and landfilling for each state. The national average transportation distance for each EOL scenario was calculated by averaging the transportation distances of individual states for each EOL scenario.

3.3 Environmental Impacts

The environmental impacts for the EOL scenarios were estimated by using data from published LCAs and life cycle inventory (LCI) databases in the LCA software SimaPro v9.5, as specified in Table 1. This data was imported into SimaPro, then modified to represent U.S.-specific production for certain processes. The environmental impacts of waste transportation were also estimated, using the distances determined previously in Section 3.2 of this research.

The 100-year carbon storage benefits were also estimated for each scenario. On average, wood is 50% carbon by mass [21], but the type of waste processing it undergoes in the EOL stage will impact how much carbon is stored per kilogram of waste processed, due to mass losses during processing or degradation of the wood over time. The 100-year carbon content was calculated by multiplying the initial carbon content by the percent of mass retained after waste processing and degradation[6]. The values for each EOL scenario were converted from kilograms of carbon to kilograms of carbon dioxide (CO_2). Substitution benefits were also estimated for the recycle, compost, and incinerate scenarios, where the end products (particleboard, compost, and electricity, respectively) were assumed to displace fossil products[7] (steel, fertilizer, and utility-generated electricity, respectively). The substitution benefit was calculated as the impact of the wood product minus the impact of the fossil product, and was calculated separately for each of the five impact categories (GWP_{100}, AP, EP, ODP, and SFP).

Table 1: Data sources used for each EOL process for wood waste.

Layer	Process Name	Data Source
Transport	Diesel-powered combination truck	[22]
Recycle	Wood recycling	[23]
Compost	Composting	[24]
Incinerate	Untreated wood (20% water) to municipal incineration	[22]
Landfill	Untreated wood (20% water) to sanitary landfill[8]	[22]

[6] Data on mass retention were taken from published LCAs and waste studies for the recycle [23], compost [24], and landfill scenarios [25].

[7] Data on environmental impacts of displaced fossil products were taken from published LCAs and waste studies for the recycle [26] [27], compost [28], and incinerate scenarios [25].

[8] The methane emission value was replaced by value reported by the Waste Reduction Model [25].

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3.4 Case Study: Disposing One Metric Ton

The environmental impacts, carbon storage, and substitution benefits of disposing of one metric ton of wood waste in the U.S. were calculated by compiling the results of the first three objectives. For example, applying the average recycling distribution to one metric ton of wood waste yielded the mass of recycled wood waste. Applying this mass to the average recycling transportation distance yielded the payload-distance (in tonne-kilometers), which was used to calculate the transportation GWP_{100}. Then, applying the mass of waste to the recycling GWP_{100}, carbon storage, and GWP_{100} substitution benefit per kilogram of waste yielded the total recycling GWP_{100}, carbon storage, and GWP_{100} substitution benefit for the recycling scenario. Summing the transportation GWP_{100} with the recycling GWP_{100} yielded the cumulative recycling GWP_{100}. This calculation was repeated for the remaining EOL scenarios and summed to yield the cumulative GWP_{100} of disposing one metric ton of wood waste. The resulting impact factor (IF) from (1) can then be applied to the mass of wood waste treated. This entire process flow was replicated for each environmental impact, since the impact categories have different units and thus cannot be summed.

$$IF = \Sigma^{n}_{i=1} D_i\,(TI_i + PI_i), \qquad (1)$$

where i = EOL scenario, n = number of EOL scenarios, IF = cumulative environmental impact factor per metric ton of wood waste for all EOL scenarios for each impact category (GWP_{100}, AP, EP, ODP, SFP), D_i = waste distribution to EOL scenario i (percentage of mass), TI_i = transportation impact of EOL scenario i, and PI_i = processing impact of EOL scenario i.

4 – RESULTS

4.1 Wood Waste Distribution

The U.S. average distribution of wood was calculated to be 10% recycled, 5% composted, 10% incinerated, and 75% landfilled, with variations in distribution among individual states. This is comparable to the national average distribution of C&D wood waste reported by the U.S. Environmental Protection Agency [29]. The EPA reported lower distribution (2-7%) to the recycle and landfill scenarios, and higher distribution (1-8%) to the compost and incinerate scenarios.

4.2 Transportation Modeling

The national average transportation distances for each scenario are shown in Figure 1. Of the four EOL scenarios, landfilling had the lowest transportation distance, due to the large number of facilities compared to other EOL scenarios. In the logistics model, there are roughly 23 times more landfills than recycling and incineration facilities, and 7 times more landfills than composting facilities. Since landfilling is the most-utilized EOL scenario for waste wood, it follows that there is more existing infrastructure for this EOL scenario.

One limitation of this study is that the transportation model assumes that waste was distributed only to the closest waste processors. The "Closest Facility" tool generates routes between a city and the closest waste processor nearby. However, a city's choice of which waste processor to partner with depends on a variety of factors other than proximity (e.g., cost, waste processing capacity, etc.). This type of data is unavailable for such a large-scale dataset, thus justifying the selection of the "Closest Facility" tool to estimate transportation distances.

Additionally, the logistics model excludes an important intermediate step in waste management: transfer stations. When waste is generated by cities, it is first sent to transfer stations, which sort the waste and then send it to its next destination (e.g., material recovery facilities for recycling). Though including this step could make this model more robust, it also has the potential to introduce more uncertainty about which transfer stations send waste to which waste processing facilities, and which transfer stations accept wood waste. As a simplifying assumption, transfer stations were excluded from the model.

Given both of these limitations, the validity of the distances generated by the "Closest Facility" tool will be evaluated further in future research, where interviews will be used to determine actual transportation distances for several large U.S. cities. This will include transportation from cities to transfer stations to waste processors or disposers.

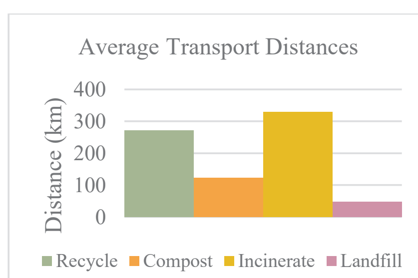

Figure 1: Average transportation distances for different EOL fates for waste wood in the U.S.

4.3 Environmental Impacts

The GWP_{100}, carbon storage, and GWP_{100} substitution benefit associated with disposing one kilogram of wood waste to each of the four EOL scenarios are shown in Figure 2. The net impact was calculated by summing the GWP_{100}, carbon storage, and substitution benefit. Lower net impacts denote more beneficial climate impacts.

The recycle scenario had the GWP_{100} highest impact, while the incinerate scenario had the lowest impact. This is because particleboard production is highly fossil-fuel-intensive and consumes resins; on the other hand, incineration produces mainly biogenic carbon dioxide, which is not included when calculating GWP_{100}. However, after accounting for carbon storage and substitution benefits, the incinerate scenario has the highest impact, while the recycle scenario has the lowest impact. Since the GWP_{100} impact includes manufacturing of new products from wood waste, it is imperative that the substitution benefits be accounted for, as substitution was used to avoid allocation of burdens between the "first" and "second" lives of wood waste in the recycle and compost scenarios.

The results of the other impact categories (AP, EP, ODP, and SFP) can be combined with the substitution benefit for that impact category. In Table 2, the sum of each impact category and its substitution benefit were calculated and ranked from 1-4, with 1 denoting the lowest impact and 4 denoting the highest. The GWP_{100} impact also includes the carbon storage benefit. This ranking is done for each of the five impact categories. The average rank for each scenario is the average of the rankings for each impact category. Here, it is shown that on average, the recycle scenario performed best across the five impact categories, while the landfill scenario performed worst.

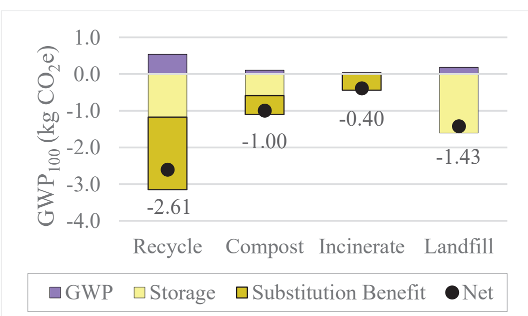

Figure 2: Emission factors (global warming potential (GWP_{100}), carbon storage, and GWP_{100} substitution benefits) for one kilogram of waste wood in different end-of-life treatments.

Table 2: Ranked results for each impact category in the four EOL scenarios.

	Recycle	Compost	Incinerate	Landfill
GWP_{100}	1	3	4	2
AP	1	2	3	4
EP	1	3	2	4
ODP	4	2	1	3
SFP	1	1	3	4
Average score	*1.6*	*2.2*	*2.6*	*3.4*

4.4 Case Study: Disposing One Metric Ton

The environmental impact results of disposing of one metric ton of wood waste in the U.S. are shown in Figure 3. These results include the cumulative environmental impact of all four EOL scenarios, the substitution benefit of displacing fossil products, and for the GWP_{100} impact only, the carbon storage benefit. The net environmental impacts (i.e., sum of cumulative environmental impacts and benefits) are shown as well. The landfill scenario is the largest contributing scenario to several impact categories (GWP, EP), while the recycling scenario is the largest contributor to others (AP, SFP).

The substitution benefits and carbon storage benefits offset the environmental impacts for a net negative impact in all impact categories except ODP. The substitution benefit of ODP was negative for the compost and incinerate scenarios, but it was positive for the recycle scenario since using particleboard instead of steel for desk manufacturing increased the ODP impacts rather than decreasing them, due to particleboard's comparatively larger ODP impact than steel. Since the ODP substitution benefit for recycling was several orders of magnitude larger than that of composting or incinerating, the cumulative substitution benefit in this impact category was positive.

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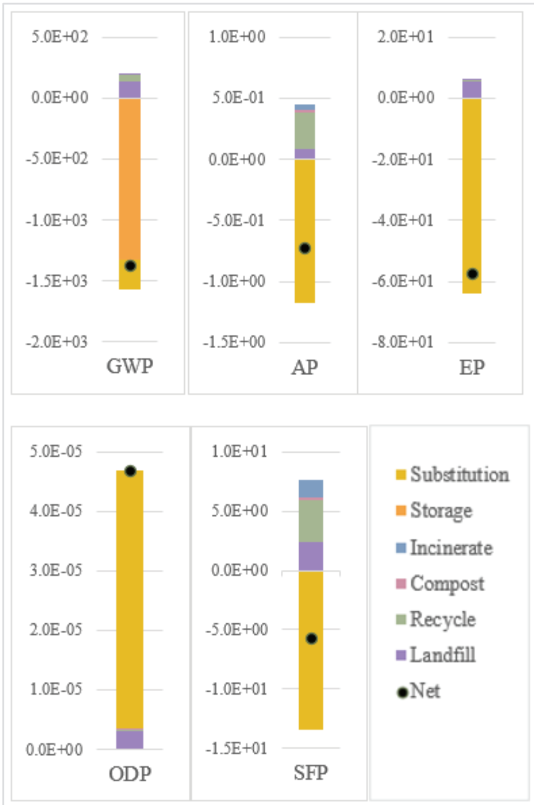

Figure 3: Results of the five impact categories, carbon storage, and substitution benefits of disposing one metric ton of wood waste in the United States. The net impact (calculated by summing all values) is represented by the black dot.

A sensitivity analysis was performed to assess the extent to which diverting wood waste from landfills could reduce the net environmental impacts. For this analysis, the waste distribution to the landfill scenario was decreased by 15%, and the diverted waste was either distributed equally to the other three scenarios ("Conservative Scenario"), or diverted only to the recycle scenario ("Optimistic Scenario") (Table 3). The percentage change in net impacts compared to the original base scenario is shown in Figure 4.

Diverting wood waste from the landfill scenario resulted in lower net environmental impacts in all impact categories, with the exception of GWP_{100} in the conservative scenario. In this scenario, the GWP_{100} increased because some of the diverted waste went to the compost and incinerate scenarios, which had higher net GWP_{100} results than the landfill scenario. However, in the optimistic scenario, the GWP_{100} was lower than the base scenario, since recycling wood produced a lower net GWP_{100} than landfilling wood does. The decreases in environmental impacts were greater than the conservative scenario in all impact categories, despite the recycling scenario's net positive ODP (Figure 3).

Table 3: Percentage of wood waste distributed to each end-of-life (EOL) scenario under three distribution cases: Base, Conservative, and Optimistic.

EOL Scenario	Base Distribution	Conservative Distribution	Optimistic Distribution
Recycle	10%	15%	25%
Compost	5%	10%	5%
Incinerate	10%	15%	10%
Landfill	75%	60%	60%

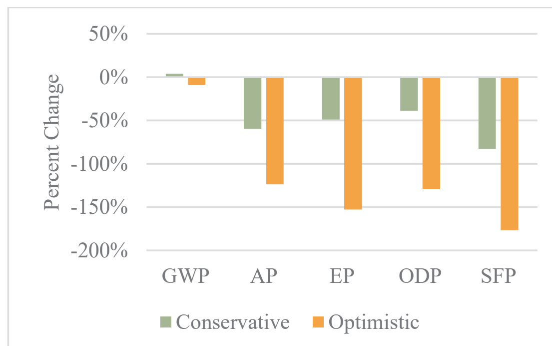

Figure 4: Percent reduction in net environmental impacts for global warming potential (GWP_{100}), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and smog formation potential (SFP) when the Conservative and Optimistic distribution cases are used instead of the Base distribution.

These results suggest that diverting more wood waste from the landfill and utilizing other waste management pathways would improve the overall environmental performance of the wood waste stream across most impact categories. The subsequent changes in net environmental impacts were sensitive to which EOL scenario the diverted waste is sent to, with the recycling scenario offering the largest reductions in all impact categories.

5 – CONCLUSIONS

This analysis estimated national-average environmental impacts, substitution benefits, and carbon storage associated with the U.S. C&D wood waste stream in four EOL scenarios: recycling, composting, incinerating, and landfilling. Assessing statewide waste characterization studies revealed that on average, the majority of wood is landfilled. Given the prevalence of this waste management strategy, the logistics model

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revealed that transporting wood to landfills had lower transportation distances (and thus, lower transportation environmental impacts) than other EOL scenarios because of the large number of C&D landfills across the country. Evaluating the GWP_{100} of waste processing and/or disposal for the four EOL scenarios determined that recycling and incinerating produced the highest and lowest GWP_{100}, respectively; this trend was reversed when substitution benefits and carbon storage were accounted for. Combining the five evaluated environmental impact categories (GWP_{100}, AP, EP, ODP, and SFP) with the substitution benefits demonstrated that the recycle scenario had the lowest average net impacts, while the landfill scenario had the highest average net impacts.

Assessing the disposal of one metric ton of C&D wood waste using the findings from this research suggests that the substitution benefits and carbon storage offset the environmental impacts associated with transportation, processing, and disposal of waste in most evaluated impact categories, resulting in net negative environmental impacts. However, the ODP impact was net positive, because the recycling substitution benefit was positive, since using recycled wood instead of steel in desk manufacturing increased the ODP rather than decreasing it. A sensitivity analysis revealed that diverting wood waste from landfills would decrease the net environmental impacts in most or all impact categories, depending on which alternative scenario was selected. Greater reductions were achieved when all of the diverted waste is recycled, even for the ODP impact category.

This research demonstrated the importance of considering substitution benefits and carbon storage, as the inclusion of these benefits changed the conclusions drawn about which waste management scenario is preferable for C&D wood waste in the U.S. Moreover, reducing the amount of waste sent to landfills could potentially reduce the environmental impacts of the waste stream in most or all of the assessed impact categories, particularly if the diverted waste is recycled. Future work will focus on expanding this research to regional levels, as it is hypothesized that regional differences in waste management, existing infrastructure, and electricity grids will drive differences in net environmental impacts across the U.S.

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