Life-cycle carbon footprint and total production potential of cross-laminated timber from California's wildland-urban interface

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Abstract

The frequency, scale, and severity of wildfires, driven by climate change, is steadily increasing in the Western United States. Sustainable forest management practices through forest thinning could reduce the impact of wildfires and provide lumber for wood-based, long-lived, and low-carbon building materials. This study explores the potential for harvesting biomass in California (CA) to mitigate wildfire risk and provide multi-decade carbon storage in the form of cross-laminated timber (CLT) for use in buildings. First, we assessed biomass resource availability finding that the total live hardwood and live softwood available in the wildland-urban interfaces (WUI) across CA sums to 14.1 million metric tons (MMT) and 34.9 MMT, respectively, which contains the equivalent of 90 MMT of atmospheric carbon dioxide. Then, we conducted a life cycle assessment of CLT considering softwood and hardwood sources to provide insights into emissions and energy demand associated with utilization of the wood removed for wildfire risk management. We found that the net life cycle carbon footprint of live hardwood and softwood when including biogenic carbon storage/emissions is 414 and 317 kg CO_2e/m^3 CLT, respectively. To incorporate the timing of these emissions and uptake, we have also conducted a cradle-to-grave time-dependent global warming potential analysis. The time-adjusted global warming potential for live hardwood and live softwood is -227 and -104 kg CO_2e/m^3 CLT, respectively. In terms of total CLT production potential, 0.03 and 0.006 million m^3 CLT can be sourced from live softwood and hardwood, respectively, in WUI in gentle slopes in CA. The resulting insights and approaches from this study are broadly applicable to other forested regions and WUIs across the U.S. and world, and provide a holistic approach to use of forest thinning as wildfire mitigation strategy in combination with a novel approach for life cycle assessment of building materials with a limited dataset.

Keywords

wildfire risk, climate change, life cycle assessment (LCA), greenhouse gas emissions, dead wood, cross-laminated timber (CLT), mixed hardwood, mixed softwood.

1. Introduction

The frequency and severity of wildfires in the western United States (US) have been increasing at an alarming rate. In 2022, forest fires emitted approximately 129.2 MMT CO_2e in the US, a 135% increase relative to 1990.(1) This increase is mainly driven by anthropogenic climate change,(2) leading to availability of live biomass and dead wood (3,4) from overgrowth of historical mismanagement. Recent California (CA) wildfires have significantly impacted the communities adjacent to wildfire-prone forests, known as the wildland-urban interface (WUI). The 2017 Tubbs fire in Northern CA that destroyed 5,600+ buildings, and the 2025 wildfire in Los Angeles are examples of catastrophic WUI wildfires in CA in recent history.(5,6) CA's wildfire mitigation agency, CALFIRE, is thinning forests through state legislation by a million acres a year to reduce the availability of wildfire fuel.(7) Additionally, the CA Governor's Office recently approved 35 high-priority logging and thinning projects in the fire-prone WUI .(8) The removal of a small percentage of dead and live wood from CA forests would reduce smoke emissions and improve fire resilience through decreasing fuel load in the forest,(9) but the state currently has a limited ability to use the resulting wood from these projects. More than half of CA's biomass-fired power plants closed after the expiration of price supports,(10) and fewer than 30 sawmills remain operational, almost 90% reduction from the state's sawmill inventory,(11) driven by unsustainable practices and environmental restrictions.(12)

A promising application for wood harvested during forest thinning for wildfire resilience is its use as cross-laminated timber (CLT), a structural building material, which was first introduced in the 1990's and began gaining in popularity in the early 2000's.(13,14) CLT can be manufactured using out-of-grade/small-diameter mixed species logs that are removed during thinning but have little to no other commercial value.(15) CLT is an engineered wood product that is lightweight, and like other bio-based building materials, it can store carbon for decades.(16–18) In part due to its fire resistance and seismic performance, CLT can be used in the construction of hybrid mid- to high-rise buildings,(19) which may enable greater adoption of prefabricated building components and reduce the GHG-intensity relative to concrete and steel.(13,20) Additionally, research has suggested that CLT can be fabricated out of mixed species of softwood and hardwood,(21) while still meeting structural requirements, although further testing and code development is needed. Studies on CLT have shown that they can be made from hardwood sourced from demolition,(22) out-of-grade lumber,(23) dead softwood timber,(24) and forest thinning and fire recovery harvests.(25) Utilizing lumber from forest thinning for CLT presents an opportunity to capture both climate resilience and mitigation benefits.

Recent literature has captured the benefits of forest thinning for wildfire risk mitigation,(9,26,27) and the GHG emission benefits of using wood-based structural timber,(16–18) but efforts analyzing the paired benefits of forest thinning for reduced wildfire risk and production of engineered lumber is still lacking. Research of building materials uses life-cycle assessment (LCA) as a means of holistically quantifying GHG emissions across a product's lifetime (i.e., "cradle to grave").(19) A previous study has shown that even with the exclusion of biogenic carbon emissions, a 26.5% reduction in GHG emissions is attainable in a hybrid CLT-based building, when compared to a concrete building.(13) There are a few prior LCA studies on CLT produced from mixed species of wood,(13,15,28) but to our knowledge, there is no previous study that combines detailed inventories of wood likely to be available from forest thinning operations with their use for CLT production from mixed species of live and dead wood.

Distinguishing between dead and live wood is important for tracking forest thinning. Dead wood may vary in its suitability for use as traditional lumber depending on the extent of rot and/or insect infestation. Dry dead wood can contribute to wildfires, especially in California, where long periods with relatively low precipitation are common. Large quantities of dead wood make management of fire events more challenging (3,4) and removing dead wood from the forest reduces the fuel load and subsequently reduces the chances of wildfire spreading. Hardwood and softwood, like dead and live wood, are distinct in their properties, composition, and range of applications. Historically, softwoods have typically been used to produce CLT, as they are cheaper and more abundant compared to hardwood. However, to provide a holistic understanding of the impact of using forest thinning as a source of CLT production, we have also considered the use of mixed hardwood for CLT manufacture.

In this study, we build on previous work(29) that underscored the importance of coordinated effort in fuel treatments for wildfire risk mitigation by developing county-level distributions of all dead wood as well as the portion of live wood in the fire-prone WUI in CA, differentiated by hardwood and softwood as well as slope of the forested land. Based on these totals and assumed removal rates, we calculated the potential CLT production from CA-based live and dead mixed wood removed in thinning. Additionally, we conducted an LCA of energy demands and net GHG emissions for CLT made from live mixed hardwood and mixed softwood. The results incorporate regional and technological variations, including terrain, differences in sawmill operations for dead and live wood, and transportation distances. The resulting insights and approaches are broadly applicable to other forested regions and WUIs across the U.S. and world, and provide a holistic approach to use of forest thinning as wildfire mitigation strategy in combination with a novel approach for LCA of building materials with a limited dataset.

2. Method

Our research included two key elements: biomass availability for CLT production and the net life-cycle GHG footprint of the resulting CLT. For the live biomass considered in this study, we only included forests that surround human communities and structures. Namely, this is the woody biomass within the WUI and within the "high"/ "very high" Wildfire Hazard Potential i.e. fire-prone.(30) Our first task was to generate county-level distributions of live hardwood and softwood in the fire-prone WUI. Using the total aboveground live biomass (> 2.5 cm (1 inch) diameter at breast height, d.b.h.) dataset for the year 2021 available from the U.S. Department of Agriculture (USDA),(31) we calculated the percentage of live hardwood (and live softwood) on forest land. We assumed that the same percentage of live hardwood (and live softwood) would apply to biomass in the fire-prone WUI. We sourced the total aboveground live biomass in the fire-prone WUI from the dataset developed for Forest Management chapter in Pett-Ridge et al. in 2023(30) We separated the amount of each type of biomass based on three slope ranges: gentle (0-20%), moderate (21-40%), and steep (>41%), as slope plays an important role in the cost and complexity of logging operations. Wood on very steep lands may be impractical to haul out for use in CLT production. Additionally, we developed the distribution of dead hardwood (and dead softwood), using the USDA dataset, on the three slopes mentioned above. Here, dead wood refers to the aboveground biomass of standing dead trees (at least 2.5 cm (1 inch) d.b.h.) on forest land.

To better understand the total CLT production potential, we estimated the number of buildings that can be made with CLT sourced from mixed wood harvesting in the CA WUI. To do this, we assumed that 1.21 m^3 of wood would be required to produce 1 m^3 oven-dry CLT, consistent with assumptions in previous literature.(15) As a reasonable upper bound for regional CLT demand, a previous study showed that the Pacific Northwest region would require 0.187 million m^3 per year by 2035.(32) This value corresponds to approximately the harvest of 0.2% of available dead wood biomass on gentle slopes in CA, which is well below removal rates considered to be sustainable. Previous studies have shown that light thinning operations (i.e. ≤33% removal of stems) can increase soil carbon stocks,(33) while another showed that clear cutting of 20.8 m^3/ha of dead logs can negatively impact biodiversity in the forest.(34) A value below the sustainable removal rate suggests that wood available from forest thinning operations could far exceed what would be needed to support the growing CLT industry. Thus, to provide a conservative estimate, we assumed that only 0.2% of the available wood biomass (live biomass in fire-prone WUI or dead biomass) would be harvested to be further processed into CLT. We have conservatively assumed only the stem wood volume of standing trees (with species at least 2.5 cm (1 inch) d.b.h.) would be used for this analysis. We have assumed 75% of the total aboveground biomass to be stem biomass.(35) To estimate the potential for this CLT to contribute to new building construction, we assumed that the total volume of CLT walls for a two-story building with a 93 m^2 (1001 ft^2) footprint would be 4.93 m^3.(36) We used this value to calculate the number of two-story buildings that can be built using the manufactured CLT for wall construction (for more details, see Table S1 and S2 in the supplementary material).

In our life-cycle GHG emissions and energy demand assessment of CLT from mixed wood, we used a decision tree framework to assign appropriate input parameters for each type of wood and harvest operation, allowing us to quantify cradle-to-gate energy and GHG impacts of producing the CLT (See Figure S1 in supplementary material for more details). Figure 1 shows the generalized process flow diagram with the system boundary considered in this study. The full details of our life-cycle inventory model are provided in Table S3. The densities of the live softwood and live hardwood were assumed to be 445 and 577 kg/m^3, respectively, at 12% moisture content by volume.(37) Input parameters for sawmill processes and CLT mill processes were also adjusted accordingly. To evaluate life-cycle GHG emissions, we used a physical units-based input-output life-cycle inventory model, Agile-Cradle-to-Grave (Agile-C2G), based on methods documented in previously published studies.(38–43) Relevant life-cycle GHG emission factors for input materials is based on previously published literature (see Table S4 in the supplementary material).(15,44–47) LCA databases including Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET),(48) U.S. Life Cycle Inventory (USLCI),(49) Ecoinvent,(50) EPA(51) were used. 100-year Global Warming Potential (GWP) values of GHGs used in this study are based on IPCC AR6.(52) We used the 2023 CAMX electricity grid mix from the U.S. Environmental Protection Agency (EPA) eGRID for assessing impacts from electricity consumption.(53) Data on emissions associated with construction and demolition phases were obtained from literature.(54,55) We selected transportation distances of 150 km and 400 km for distances from harvest site to sawmill, and sawmill to CLT mill, respectively. We chose a distance of 150 km and 100 km for transportation of CLT from CLT manufacturing mill to construction site, and from demolition site to end-of-life (EoL) destination, respectively. For more information on transportation distances, see supplementary material. Here, we have assumed a 50-year service life during the use phase. At the EoL stage, we assumed that the CLT from the demolition process will be combusted in a biomass power plant, consistent with assumptions in Van Roijen et al.(55)

Additionally, to understand the sensitivity of the results to key uncertain parameters, we presented two additional cases: an optimistic and pessimistic case for each type of hardwood and softwood considered for the life-cycle GHG and energy demand assessment. In the optimistic case for each scenario, we have considered harvest using clear-cut method and a projected 2035 electricity grid mix for California.(56) Additionally, to provide an upper and lower bound estimate of impact of wood source density, we have varied the wood density in the optimistic/pessimistic case studies, based on the abundance of specific species of wood in California.(31) See supplementary material Table S5 for more details on the sensitivity analysis parameters chosen in this study.

Given the multidecade time horizons for building materials, to determine time-sensitive impacts on cumulative radiative forcing, we have also calculated the emissions at each phase of the life cycle using time-adjusted warming potentials (TAWPs). We have used the dynamic accounting of carbon uptake in the built environment (D-CUBE) tool developed by co-authors for TAWP analysis.(55).

We have also provided a quantitative analysis of the use of dead wood as a source for CLT manufacturing. It is worth noting that the cause of death, wood species, and decay class will substantially impact the density of the sourced wood.(57) For the purposes of the present study, densities of 334 kg/m^3 and 473 kg/m^3 were assumed for dead softwood and dead hardwood, respectively, at 12% moisture content, based on personal communications with sawmill operators, and a review of literature of dead wood densities.(57,58)

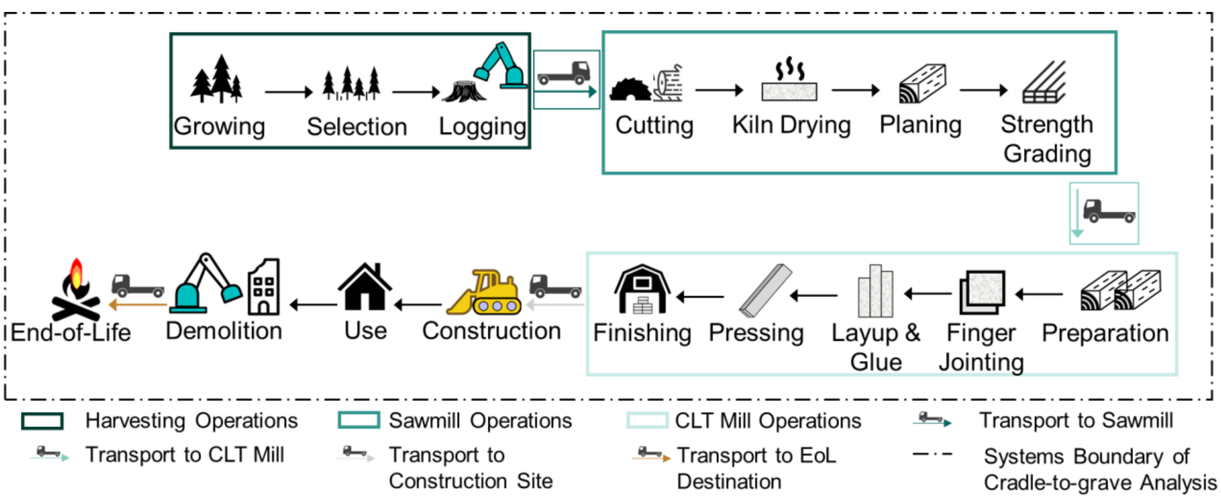

Figure 1. A generalized process flow diagram displaying the system boundary for the life cycle CO_2e and energy demand assessment conducted in this study.

Additionally, we have considered carbon uptake during biomass growth and biogenic CO_2 emissions from burning of wood waste during processing to generate energy and combustion of CLT at the EoL. We estimated temporary carbon storage in live wood based on the wood density at 12% moisture content and an assumed carbon concentration of 50% of total wood.(59) Because our feedstock is essentially a waste product from sustainable forest management, we treat it as “burden-free” which is a conventional assumption in LCA. The forest carbon flux is highly dependent on natural disturbances (such as extreme weather events, pest infestation and diseases), time horizon of interest and whether climate benefits of avoided emissions are accounted for when considering wood products.(30) These factors in turn are influenced by forest-management practices and would vary on a case-by-case basis, and thus are outside the scope of the present study.

3. *Results*

Figure 2 shows the amount of aboveground live softwood and hardwood in fire-prone WUI forest land in CA. The available live hardwood biomass increases as slope increases, with a total of 2.7, 3.8, and 7.6 MMT of biomass distributed in gentle, moderate, and steep slopes, respectively. Live softwood biomass, which is more conventionally used for CLT, is both more abundant than live hardwood and distributed more uniformly among slopes considered in this study. A total of 12.2, 11.3, and 11.3 MMT of live softwood biomass is distributed in gentle, moderate, and steep slopes, respectively.

One potential means of controlling wildfire spread might be to prioritize thinning in counties where the live tree biomass totals in the fire-prone WUI are high, and the counties are also at highest risk for wildfires. Toulumne county has the 4th highest amount of live softwood biomass (2.0 MMT) in the state, while San Diego county has the third largest amount of live hardwood biomass (0.74 MMT). Both these counties are among the 10 counties in CA with the highest risk of wildfires.(60)

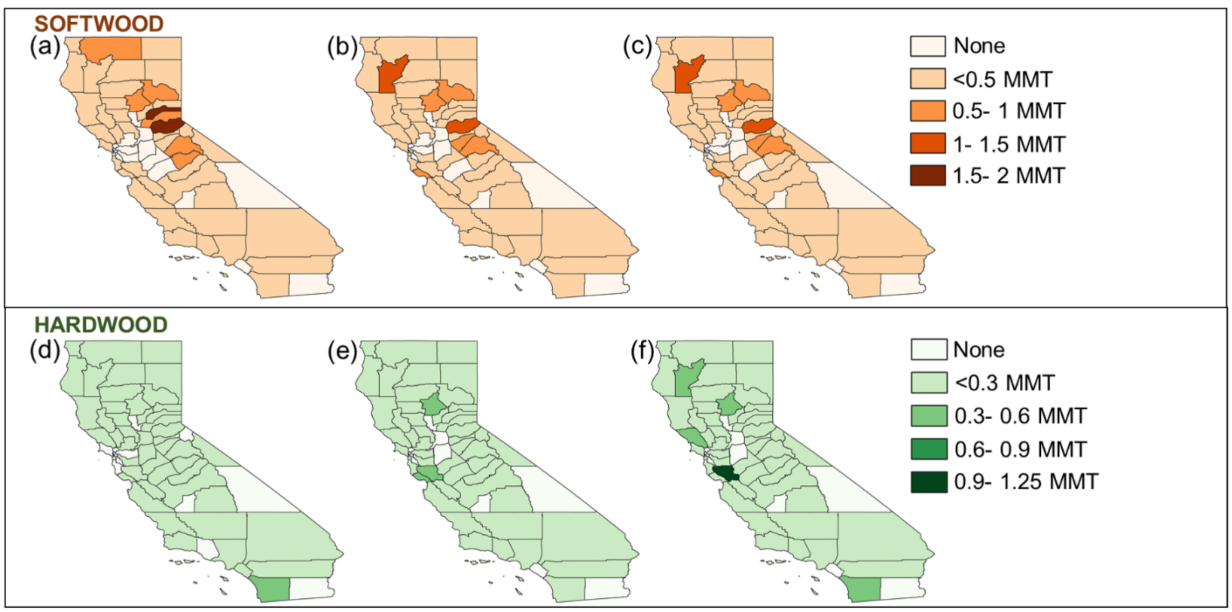

Figure 2. Aboveground live biomass (million metric tons, MMT) in fire-prone wildland-urban interface (WUI) in various slopes. Maps a and d: gentle slope, maps b and e: moderate slope, and maps c and f: steep slope.

Figure 3 shows the aboveground dead softwood in terms of hardwood and softwood in various slopes. The distribution of dead softwood in CA over various slopes considered in this study is similar: with a total of 60, 59, and 67 MMT distributed in gentle, moderate, and steep slopes, respectively. A total of 4.6 MMT of dead hardwood are distributed in gentle slopes, while another 8.5 and 17.8 MMT of dead hardwood are dispersed in moderate, and steep slopes, respectively.

The lower amount of hardwood biomass (live/dead), when compared to softwood, is unsurprising, since CA forests are dominated by softwood trees, while hardwood trees are usually scattered as individuals and small groups.(61) The substantially lower hardwood totals when compared to softwood, along with the higher concentration of hardwood biomass on steeper slopes, suggest that typical thinning operations would result in mostly mixed softwood (live/dead).

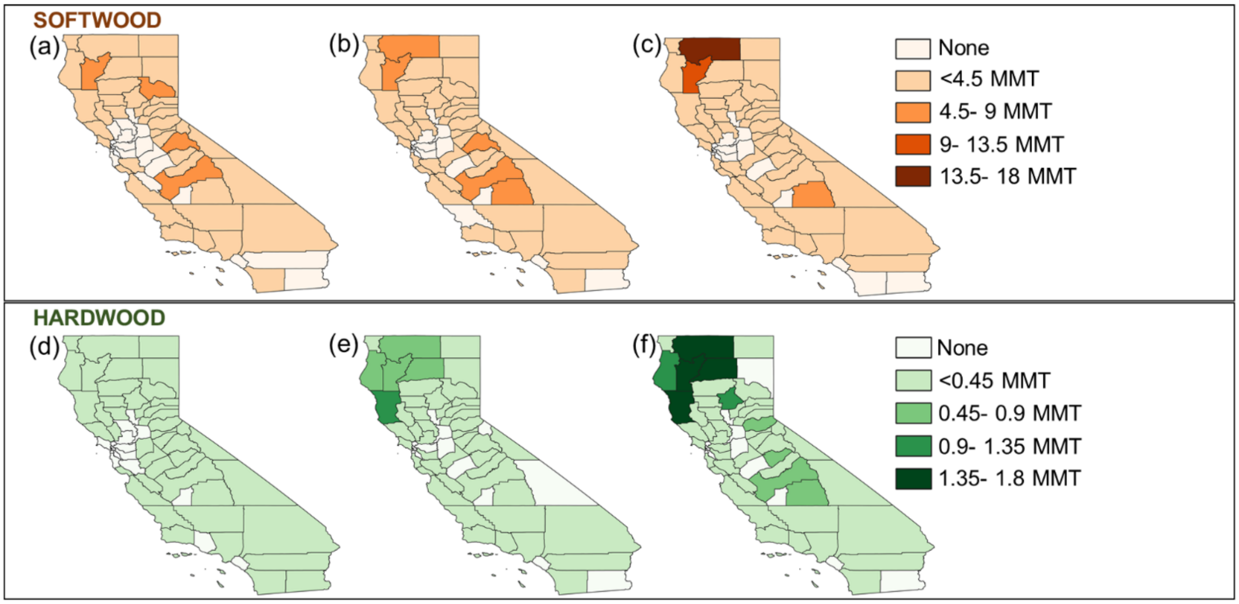

Figure 3. Aboveground dead biomass (million metric tons, MMT) in various slopes. Maps a and d: gentle slope, maps b and e: moderate slope, and maps c and f: steep slope.

Figure 4 depicts the amount of CLT that can be fabricated from using 0.2% of the available live and dead biomass from various slopes. Harvesting dead wood stem from gentle slopes will result in 0.01 and 0.22 million m^3 of CLT from dead hardwood and softwood, respectively. This biomass can contribute to the wall construction of 2,445 and 45,171 two-storied buildings if made from dead hardwood and softwood, respectively. Similarly, if 0.2% live wood from fire-prone WUI forests are harvested from only gentle slopes, 0.006 and 0.03 million m^3 of CLT can be manufactured from live hardwood and softwood, respectively. This quantity of CLT has the potential to be used in the manufacture of walls for a total of 8,064 two-storied buildings.

Although in recent times the demand for CLT-based buildings in CA has been increasing, there is still a lack of infrastructure to manufacture CLT locally. Over 600 homes in Greenville, Plumas county were destroyed by the Dixie wildfire in 2021, and currently CLT-based residential buildings are being built for the residents using wood sourced from Oregon.(62) Using our analysis approach, only 0.03% of the dead wood stem biomass needs to be harvested from Plumas county to build 670+ two-story buildings with CLT walls. This finding indicates that, with the establishment of a small-scale CLT manufacturing industry, even the locally available scorched wood from wildfire-affected communities can be adequate to rebuild the housing. Additionally, it emphasizes that even though the 0.2% removal rate assumed in this study is small, the impact from the sourced wood conversion to CLT would have substantial impact in housing and creating jobs for the local communities.

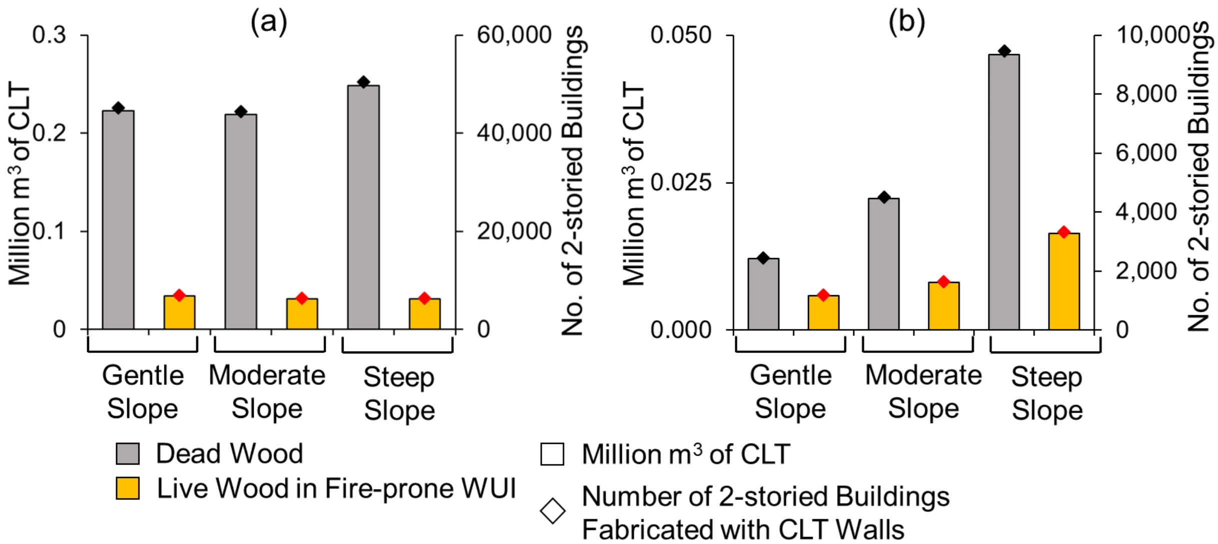

Figure 4. Amount of CLT manufactured (in million m^3) and the total number of CLT-wall containing 2-storied buildings that can be fabricated from utilization of 0.2% of the available live and dead biomass in CA from (a) softwood and (b) hardwood.

Figures 5 shows the life-cycle GHG emissions and the energy demand, for the creation of 1 m^3 of CLT made from mixed hardwood and mixed softwood. Among the various stages of processing considered in this study, sawmill operations contribute to 13% and 25% of total emissions for live hardwood and live softwood, respectively. In terms of energy demand, again sawmill operations contribute to a substantially large portion of the total energy demand (45%) to manufacture 1 m^3 CLT from live softwood. However, for live softwood, 64% of the energy demand during sawmill processing is met with wood waste generated onsite, which aligns with results from other studies.(63) For live hardwood, wood waste contributes 21% of the fuel used to meet the energy demand of the sawmill processing step. The sawmill residues as a fraction of total wood processed for hardwood is generally lower for other applications,(64) but its use in CLT manufacturing is so far very limited, as is the availability of real-world data. The life-cycle GHG emissions value for live hardwood sawmill operations obtained in this study is than that found in previous literature,(45) driven in part by our use of the CAMX grid mix, in addition to the fuel amounts and biogenic CO_2 emissions from wood waste adjusted based on the amount of dried lumber utilized and location of study.(11) GHG emissions and energy demand for processing mixed live softwood in sawmills are consistent with values for softwood lumber preparation in previous studies.(46,63–66)

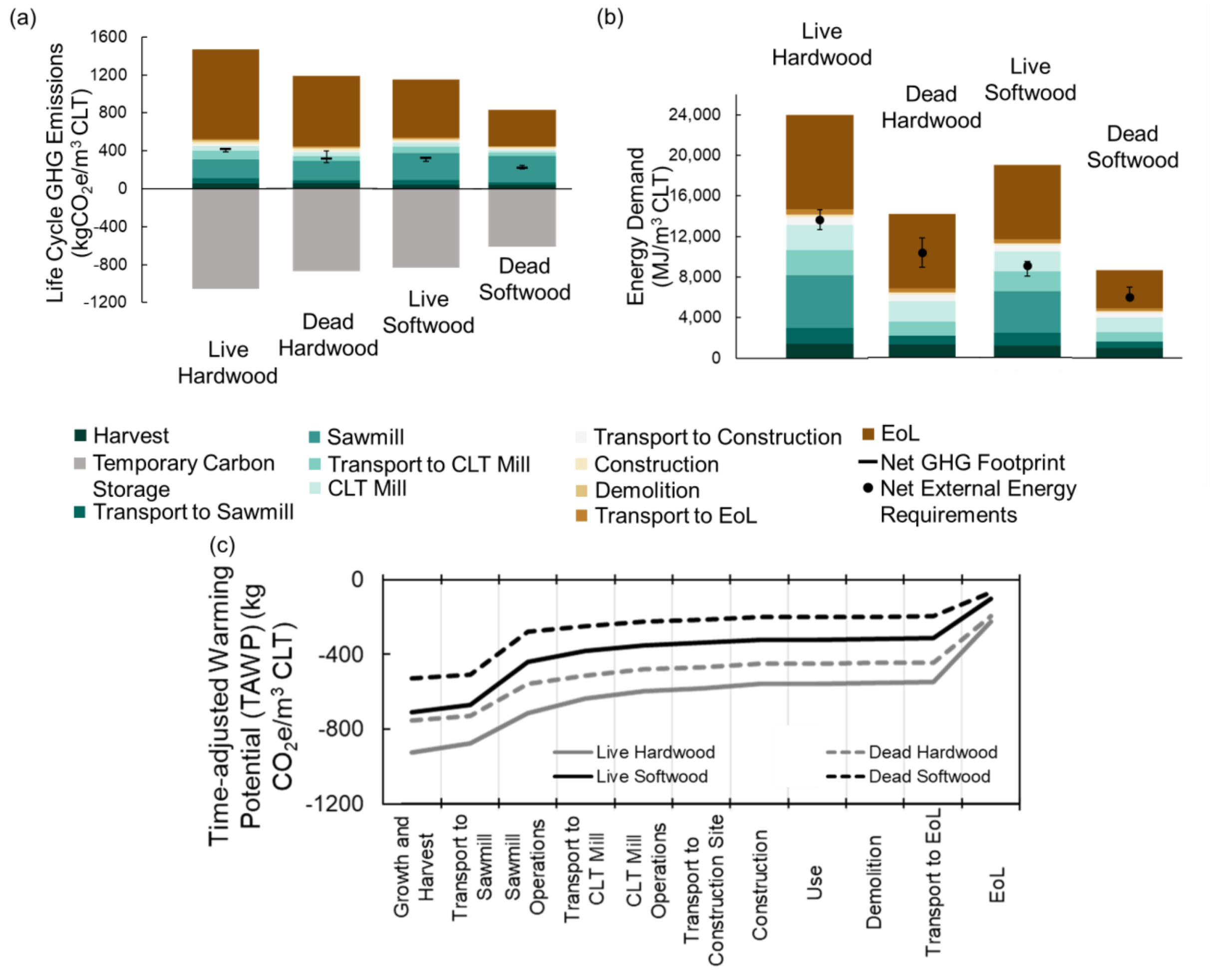

Figure 5. (a) Life cycle GHG emissions (kg CO_2e/m^3 CLT) (b) energy demand (MJ/m^3 CLT) and (c) life cycle GHG emissions (in terms of TAWP) of CLT made from mixed hardwood and mixed softwood. The bars in (b) show total energy demand, and the scatter plots show the net energy demand after accounting for energy generated onsite by the burning of wood.

As shown in Figure 5, the life cycle GHG footprint of harvesting live hardwood and softwood is 54.6 and 46.5 kg CO_2e/m^3 CLT, respectively. The higher CO_2e emission per m^3 of CLT for hardwood, when compared to softwood, is due to the increased fuel and equipment use necessary for hardwood logging operations. Harvesting operations are largely dependent on the type of equipment used during felling of trees. For slopes less than 30%, feller-buncher felling is recommended as a more efficient choice than chainsaw felling.(67) If harvest from steeper slopes (not included in our analysis) is desired and a chainsaw-based harvesting system is utilized, the life cycle GHG emissions of the harvesting operations would decrease by 12% and 9% for live hardwood and live softwood-based CLT, respectively. This difference is due to the use and maintenance of chainsaw-based systems being less fuel intensive, when compared to feller-buncher-based systems. However, studies including steeper slopes must also consider additional fuel usage and more complex equipment to haul the logs from steeper slopes to sawmills, which would increase the overall GHG footprint and energy demand of 1 m^3 of CLT production.

For live hardwood-based CLT, it can be estimated that 1 m^3 of CLT stores carbon equivalent to 1057 kg CO_2e (100-year GWP) based on the wood content of a finished panel with 515 kg/m^3 dry density, a 12% moisture content and a carbon content of 50%. From this, the net cradle-to-grave GHG footprint is approximately 414 kg CO_2e for 1 m^3 of CLT. For live softwood-based CLT, 1 m^3 of CLT stores the equivalent of 816 kg CO_2e, and the net life cycle GHG footprint is approximately 317 kg CO_2e/m^3 CLT. In our study, we have assumed the combustion of CLT at EoL. Various other options for the utilization of CLT at the EoL have shown that the EoL emissions can be reduced based on the chosen method of disposal, which in turn will impact cradle-to-grave life cycle emissions.(55)

The use of dead softwood, instead of live softwood, to manufacture CLT results in a net cradle-to-grave GHG footprint of 214 kg CO_2e for 1 m^3 of CLT. Dead softwood processing at sawmills contributes to a substantial amount of life cycle GHG emissions (22%) and the energy demand (57%) of 1 m^3 CLT production, similar to the results obtained for CLT manufacture from live softwood processing. However, the dead wood waste generated on-site is able to meet 70% of the on-site energy demand at the sawmills. This slightly higher value, compared to the wood waste contribution to energy demand of live softwood processing, is due to the higher heat of combustion of dead wood.(68) For the manufacture of 1 m^3 CLT using dead hardwood, the net cradle-to-grave GHG footprint is approximately 306 kg CO_2e.

To account for dynamic effects of the timing of emissions and uptake on the global warming potential, we have also analyzed the time-adjusted global warming potential (TAWP) for each source of wood considered in this study. When accounting for the dynamic effects of GHG fluxes via TAWPs, CLT sourced from live hardwood and live softwood result in sequestration of −226 and -104 kg CO_2e/m^3 over the life-cycle, in contrast to the positive values discussed above for GHG emissions from conventional global warming potential (on a 100-year basis) assessment. The use of TAWP takes into account the dynamic effects of early CO_2 uptake and carbon storage during use phase, and is helpful in highlighting the beneficial effects of CLT on cradle-to-grave life cycle GHG fluxes. Furthermore, the results show that use of higher density/hardwood species for CLT production have the potential to offset the total amount of cradle-to-grave emissions associated with the final product, depending on the EoL disposal option chosen; although, the longevity of carbon storage in CLT is likely to be lower than that from more permanent storage, such as geologic carbon dioxide sequestration.(30)

4. Discussion

This study highlights the potential for biomass from wildfire resilience and forest thinning operations to be used for manufacturing CLT, and the associated benefits of carbon storage potential of the manufactured products. However, it is also important to note the local capacity to process the wood. In 2024, a total of 26 wood processing mills are operational in CA (see Figure S2 in supplementary material),(69) although there are over 8 million metric tons of annual removals of above ground biomass in the state.(70) The limited number of sawmills means that the cost and associated GHG emissions of transporting logs for further processing is high. Our study considers a removal rate of 0.2% of live and dead biomass, based on CLT demand and manufacturing capacity in California. However, typical thinning operations can exceed 50% in some areas to effectively mitigate wildfire risk.(71) This wide gap between the magnitude of potential wood supply and demand for CLT suggests that early production could focus exclusively on the wood most economical to collect and haul to CLT mills, with future growth expanding supply to areas that are less accessible. For the time being, we have limited our assessment to a removal rate that could be realistically tied to CLT demand and supply capacity in California, but future work could consider the impacts and benefits of significantly higher removal rates – such as removed fuel for bioenergy resources.(72) Currently, there are efforts to assess local biomass availability, quantify risk, and spur investment in infrastructure capable of processing the material, such as the Bioeconomy Development Opportunity Zone Initiative.(73) Additionally, public campaigns and workshops on rebuilding communities impacted by wildfire with CLT, such as those proposed by Sierra Institute,(74) would aid in public awareness regarding the benefits of CLT in mass housing in wildfire-prone areas and creation of job opportunities. However, based on the future demand for CLT and the decarbonization of the building materials sector, the mitigation potential for biomass will vary, and will in turn impact forest thinning removal rates for conversion into building materials. Future work could focus on how sectoral decarbonization over time influences cradle-to-grave emissions of CLT.

This study indicates that the type of wood matters in the energy and GHG balance of CLT production. Processing hardwood is potentially more GHG-intensive and costlier than processing softwood into CLT. Our aim was to assess the potential for usage of out-of-grade or small diameter hardwood that would not be used in other wood-based products. Additionally, if the proximity of the sawmill to the CLT mill is close, the transportation impact of GHG emissions could compensate for the emissions associated with the processing of hardwood/higher density lumber. However, it is worth noting that none of the operational wood processing mills in CA in 2024 report processing of any hardwood species. Given that CA is one of the leading consumers of hardwood lumber,(75) exploration of the ability for sawmills to process hardwood into engineered wood products locally would not only reduce transportation-related emissions, but also reduce the overall GHG footprint and cost of CLT production. CLT’s ability to provide fire resistance(76) sets it apart from other lumber products that are commonly used as building materials in CA.

In this study, we primarily considered the GHG footprint of biomass harvesting from gentle slopes. Where slopes are steep or the weather is harsh, mechanized felling or cable yarding systems are recommended, instead of ground-based harvesting systems, but is beyond the scope of the current study and likely presents additional costs worthy of their own dedicated study. Utilization of such systems would not only impact energy demand and life-cycle GHG emissions of the harvesting stage, but might also potentially impact subsequent transport and sawmill processing. A semi-mechanized system has been shown to have reduced GHG emissions than fully-mechanized systems,(77) and can be explored in future studies on the impact of slope on emissions associated with harvesting operations. Furthermore, forests are vital in contributing to the ecosystem and biodiversity of a region, and harvesting operations and forest management strategies should aim to conserve biodiversity of a habitat.(30) Additionally, moisture content, and hence sawmill operations of processing dead wood would depend on the cause of death and the age of the dead wood, among other factors. Cause of death would also impact whether the dead wood could be utilized for processing into CLT (in terms of structural performance requirements). Moreover, the future adoption of a decarbonized energy grid would further reduce the GHG footprint. These factors, although important to consider, are outside the scope of present study.

5. *Conclusion*

This study highlights the potential for biomass from forest thinning operations to be used for manufacturing engineered wood products and the net near-term carbon storage potential of those materials. The approach applied to forests in CA can be used to estimate potential across the U.S. and globally. However, an important caveat to these estimates of CLT production and carbon storage potential is that realizing them requires that sustainable forest thinning operations proceed as needed and that local capacity exists to receive and process the wood.

The results of this study serve as a reminder that there are several potential fates for forest residues, and future studies could offer valuable insights by estimating the cost and emissions tradeoffs of implementing pile burning, use of forest residues for bioenergy/pellet production, use of forest residues for CLT production, and other applications. Based on the CA-specific results, the distribution of biomass could be used to prioritize the establishment of new sawmills.

While the uncertainties mentioned above are important to consider in refining our LCA and CLT manufacturing results, our study highlights the substantial benefits of harvesting lumber from high-risk wildfire regions: wildfire resilience for forests and at-risk communities, GHG emission reduction by avoiding wildfire emissions and promoting the use of low-carbon building materials, and increasing the availability of local building materials to support needed housing development. Future research could focus on working with policy makers to implement pilot programs and monitor these benefits to better capture the barriers and opportunities for improvement in this wildfire resilience program.

Supplementary Material

Additional methods details, including life cycle inventory inputs and plot of location of operational wood-processing mills in 2024 (DOC).

Acknowledgement

This work was funded through the US Department of Energy, Advanced Research Projects Agency–Energy (ARPA-E, Grant #DE-AR0001625) in FY23. This article represents the views of the authors, not necessarily those of the funder. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, through contract DE-AC02-05CH11231 between Lawrence Berkeley National Laboratory and the U.S. Department of Energy. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes. The authors thank Sara Keubbing and Reid Lewis from Yale University for sharing the data on aboveground living biomass in the fire-prone wildland-urban interface in California and the Woody Biomass Utilization Group at University of California for the wood processing facilities dataset.

Declaration of interests

C.D.S. has a financial interest in Cyklos Materials.

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Life-cycle carbon footprint and total production potential of cross-laminated timber from California's wildland-urban interface

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Supplementary Material

Table S1: Amount of CLT manufactured (in m^3) and the total number of CLT-walls containing 2-storied buildings that can be fabricated from utilization of 0.2% of the available dead wood biomass in California from hardwood and softwood.

Type of Wood	0.2% of total stem wood volume of standing dead trees on forest land (Million metric ton)*			Total amount of CLT that can be manufactured (Million m^3)			No. of buildings (93 m^2 footprint) with CLT walls		
	Slope (%)			Slope (%)			Slope (%)		
	Gentle	Moderate	Steep	Gentle	Moderate	Steep	Gentle	Moderate	Steep
Hardwood	0.007	0.013	0.027	0.01	0.02	0.04	2,445	4,518	9,462
Softwood	0.09	0.09	0.10	0.22	0.22	0.25	45,171	44,418	50,441

*Based on total stem wood volume of standing dead trees (timber species at least 1-inch diameter at breast height, d.b.h.) on forest land in California.[1]

Table S2: Amount of CLT manufactured (in m^3) and the total number of CLT-wall containing 2-storied buildings that can be fabricated from utilization of 0.2% of the available live wood biomass in fire-prone WUI in California from hardwood and softwood.

Type of Wood	0.2% of total stem wood of standing live trees on forest land in fire-prone WUI (Million metric ton)			Total amount of CLT that can be manufactured (Million m^3)			No. of buildings (93 m^2 footprint) with CLT walls		
	Slope (%)			Slope (%)			Slope (%)		
	Gentle	Moderate	Steep	Gentle	Moderate	Steep	Gentle	Moderate	Steep
Hardwood	0.004	0.006	0.011	0.005	0.008	0.016	1,170	1,639	3,325
Softwood	0.02	0.02	0.02	0.03	0.03	0.03	6893	6385	6385

*Based on total stem wood volume of standing live trees (timber species at least 1-inch d.b.h.) on forest land in California.[1][2]

Table S3: Life cycle inventory inputs for each stage of processing to produce 1 m^3 of CLT.

Processing Stage	Input Parameter	Unit	Live Mixed Hardwood	Live Mixed Softwood	Notes
Harvesting Operations	Equipment	kg	0.48*	0.37*	*include both use and maintenance
	Gasoline	MJ	35.9	24.6	
	Diesel	MJ	263.1	192.4	
	Lubricant	kg	0.4	0.3	
Sawmill Operations	Coal	MJ	–	295.8	
	Natural Gas	MJ	611.4	181.3	
	Gasoline	MJ	20.3	–	
	Diesel	MJ	203.7	–	
	Oil	MJ	0.7	239.6	
	Wood	MJ	1069.4*	2548.3*	*residues from sawmill operations
CLT Mill	Resin	kg	6.2	6.1	
	Electricity	MWh	0.1241	0.1229	
	Natural Gas	MJ	96.3	95.4	
Construction	Electricity	MJ	243	187	[3]
Demolition	Diesel	L	0.42	0.32	[3], [4]
Transportation to Sawmill	Flat Bed Truck	km	150	150	
	Logs Transported	kg	1173	906	
Transportation to CLT Mill	Flat Bed Truck	km	400	400	
	Logs Transported	kg	698	539	
Transportation to Construction Site	Flat Bed Truck	km	150	150	
	CLT Transported	kg	577	445	
Transportation to EoL Processing	Flat Bed Truck	km	100	100	
	CLT Transported	kg	577	445	

Table S4: Life-cycle GHG intensities for the life cycle inventory inputs used in this study.

Parameter	Life-Cycle Emission Factor					References
	CH_4	**NO_2**	**CO_2**	**CO_2e**	**Unit†**	
Equipment	--	--	--	46.6	kg/dry ton wood	[5]
Gasoline*	1.4E-04	8.0E-07	1.0E-01	--	kg/MJ	Upstream emissions calculated using AgileC2G and data from Nordahl *et al.* 2023.[6] Combustion emissions are calculated using data from EPA 2024.[7]
Coal*	1.6E-04	1.5E-06	9.4E-02	--	kg/MJ	
Oil*	9.2E-05	6.2E-07	7.7E-02	--	kg/MJ	
Natural Gas*	1.1E-04	3.3E-08	5.9E-02	--	kg/MJ	Upstream and combustion emissions calculated using AgileC2G and data from Nordahl *et al.* 2023.[6]
Diesel*	1.1E-04	1.1E-06	9.3E-02	--	kg/MJ	
Lubricant	4.9E-04	2.7E-06	1.9E-01	--	kg/kg	[6]
Wood	9.6E-03	4.2E-03	1.8⁎	--	kg/kg	[8]
Resin	2.1E-03	1.8E-04	5.6E-01	--	kg/kg	[6]
Electricity	1.4E-05	2.1E-04	2.3E-01	--	kg/KWh	[9]
Flat Bed Truck	2.7E-04	6.4E-07	2.1E-01	--	kg/Mt-km	[6]

*Includes both upstream emissions and combustion emissions.

†Units for the emission intensities are kg of pollutant per unit of the parameter indicated in the unit column.

⁎Emissions associated with biogenic carbon

Table S5: Optimistic and pessimistic scenario inputs used in this study.

	Optimistic Scenario Notes*	Pessimistic Scenario Notes*
Live Hardwood	Harvest using clear-cut method. Density of wood: 507 kg/m^3 assumed based on the abundance of low-density bigleaf maple in CA. Decarbonized electricity grid projected in 2035.[10]	Density of wood: 675 kg/m^3 assumed based on the abundance of tan oak in CA.
Live Softwood	Harvest using clear-cut method. Density of wood: 370 kg/m^3 assumed based on the abundance of low-density incense cedar (IC) and capability of operational sawmills to process IC in CA. Decarbonized electricity grid projected in 2035.[10]	Density of wood: 480 kg/m^3 assumed based on the abundance of Douglas fir in CA.
Dead Hardwood	Harvest using clear-cut method. Density of wood: 391 kg/m^3 assumed.[11] Decarbonized electricity grid projected in 2035. [10]	Density of wood: 574 kg/m^3 assumed based on conversations with local sawmills.
Dead Softwood	Harvest using clear-cut method. Density of wood: 314 kg/m^3 assumed based on conversations with local sawmills. Decarbonized electricity grid projected in 2035. [10]	Density of wood: 381 kg/m^3 [11] assumed based on the abundance of pines in CA.

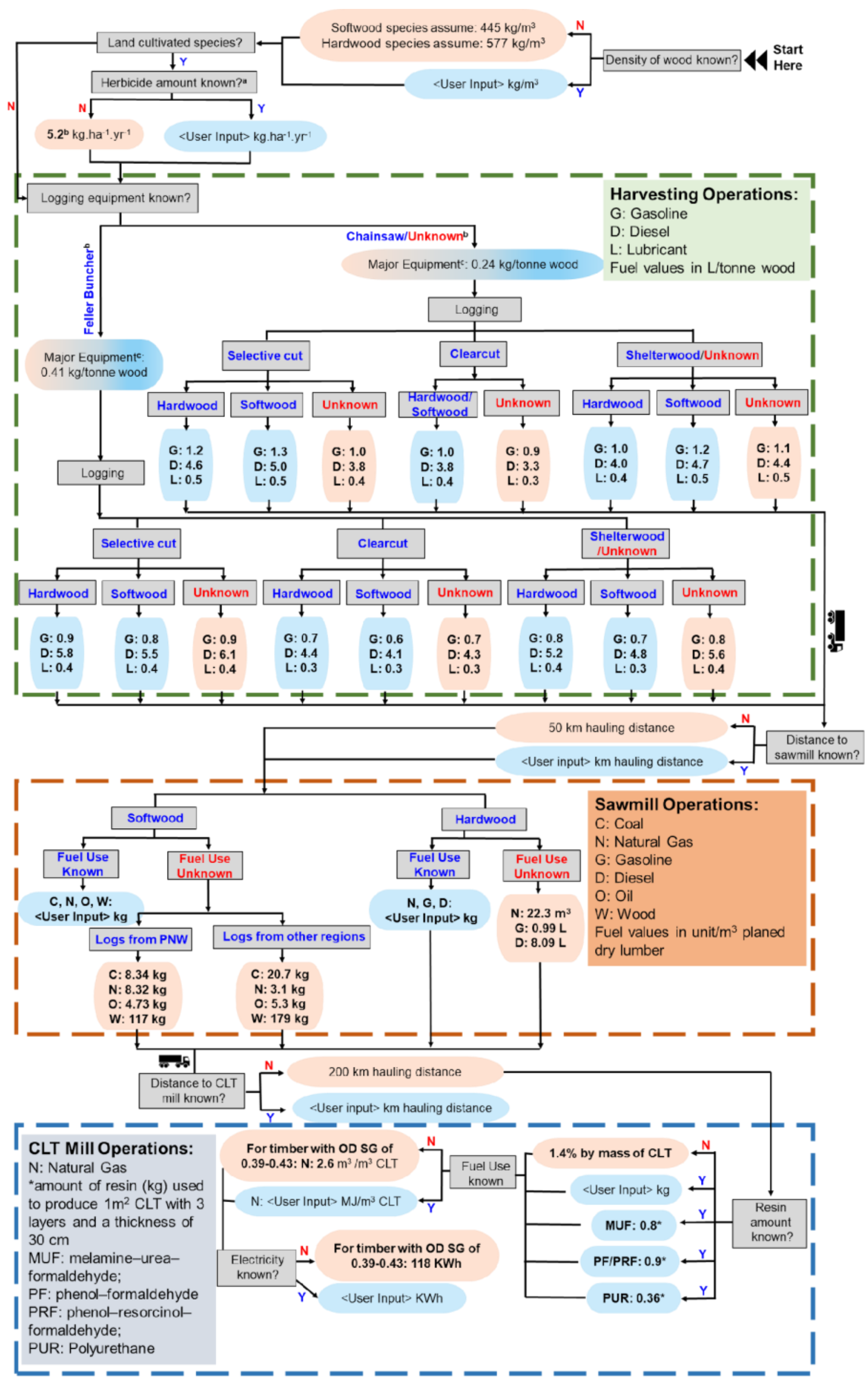
*LCI inputs for harvesting, sawmill and CLT mill operations were adjusted accordingly.

Table S6: Input data for time-adjusted warming potential assessment.

Life cycle stage	**CO_2e for live hardwood(kg/m^3 CLT)**		**CO_2e for live softwood(kg/m^3 CLT)**		**Time* (years)**
	Fossil	**Biogenic**	**Fossil**	**Biogenic**	
Growth and Harvest	54.6	-1057.8	46.5	-815.8	21
Transport to Sawmill	57.5	--	44.4	--	0
Sawmill Operations	88.1	109.0	63.1	216.0	0
Transport to CLT Mill	91.2	--	70.5	--	0
CLT Mill Operations	49.1	--	37.9	--	0
Transport to Construction Site	18.2	--	14.0	--	0
Construction	25.7	--	19.9	--	1
Use	--	--	--	--	50
Demolition	17.7	--	13.6	--	1
Transport to EoL	12.1	--	9.4	--	0
EoL	--	949.0	--	600.0	1

*Consistent with assumptions in Van Roijen et al. [12]

Figure S1: Decision tree of the developed framework for CLT manufacture.



[a]Herbicide is assumed to be comprised of 25% atrizine, 25% metolachlor, 25% acetochlor and 25% cyanazine by mass (kg).
[b]If the sawmill is a medium-sized one, assume use of feller buncher-based harvesting system for logging operations. If sawmill size is unknown, or logging equipment information unknown, assume use of chainsaw-based harvesting system.
[d]Major harvesting equipment considerations include both use and maintenance of the harvesting equipment when calculating impact on GHG emissions.

The framework developed is expected to be used for estimating life cycle GHG footprint of 1 m^3 of CLT produced from wood that has limited amount of data availability/unknown parameters.

Lumber may be produced from a wide variety of tree species grown in the native region and has different densities depending on the raw materials mix. The minimum specific gravity (SG) requirement of lumber for CLT manufacturing is 0.35.[13]

- Material formation and harvesting

Growing and collection operations (e.g., logging) are significant parameters affecting GHG fluxes for biogenic materials. For the environmental impacts associated with wood harvest and transport operations, the LCI data were based on the cradle-to-gate inputs and outputs of previously published literature,[5], [14] and LCA databases including Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET),[15] U.S. Life Cycle Inventory (USLCI),[16] Ecoinvent,[17] Environmental Protection Agency (EPA),[7] to incorporate material inputs for harvesting stage. In this study, unless otherwise noted in Table S5, consistent with best-practices for thinning operations, we modeled a selective cutting method for logging. Furthermore, we assumed that logging would be conducted on gentle slopes (0-20%) using a feller buncher-based harvesting system (comprising feller bunchers, chainsaws, skidders and knuckleboom loaders).[5][2]

- Processing of raw materials

Using biogenic material properties and final properties of the product, mass flows can be estimated. Kiln-dried and sawn lumber is the wood input for CLT. The output from the sawmill is finished logs. The sawmill processing steps include all debarking, sawing, chipping, and grinding required to convert the logs to rough dry lumber. The wood waste generated during the process is used in generating energy onsite. As with other processes, the sawmill operational energy demand cannot readily be directly linked to the biogenic resource characteristics, so data related to processes involved in the sawmill were adapted from the Pacific Northwest region.[8], [18]

- Material manufacture and assembly

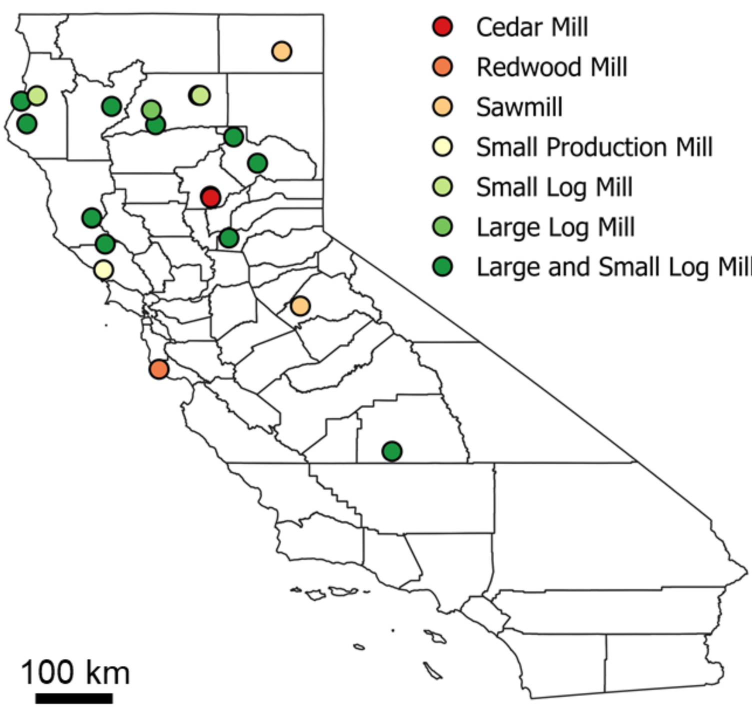
While processed raw resources, such as sawn lumber, can be a final biogenic product, in many engineered biogenic materials, additional component production is needed. These additional stages of processing can lead to GHG emissions. For CLT, the main product in the manufacturing process is comprised of wood and resin. Electricity and fuel requirements for CLT manufacturing will depend on technology, efficiency, and available equipment at the CLT mill, and as such variations due to location and size of the CLT mill is expected. Resin is required in both the finger jointing and the face bonding processes, while natural gas is required for lumber drying. Electricity is the main energy input for operating the equipment used in the production processes. The quantity of co-products from CLT manufacturing were adapted from literature[19], [20] and values were adjusted based on the amount of production relative to this study.

- Transportation

The transportation-related GHG emissions and associated energy demand are directly dependent on the distance traveled. Based on the currently operational wood processing mills' location in

CA (see Figure S2) and a review of literature,[21] we selected a transportation distance of 150 km from harvest site to sawmills. It is expected that CLT mills would be built near construction sites to reduce cost of prefabricated CLT transportation. Thus, the likelihood of CLT mills being closer to large cities, where there is a greater need for construction of CLT-based structures, is higher. Chen et al. studied transportation logistics of CLT in Washington, and their study considered a range of distances of CLT mill from sawmill between 21 to 440 km.[19], [20] With a limited number of sawmills in CA, and further limitations in their ability to process different species of wood, we selected a distance of 400 km from sawmill to CLT mill, to provide an upper bound of estimate for transport-related emissions. Additionally, we assumed a distance of 150 and 100 km for transport of CLT from the mill to the construction site and from the demolition site to the end-of-life processing, respectively, based on literature review.[19], [20], [22] Our model assumes a flatbed truck for transportation of lumber.

Figure S2: Location of operational wood processing facilities in California in 2024 based on data provided by Woody Biomass Utilization Group, University of California Agriculture and Natural Resources.[23]



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