sustainability

Article

Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration

Maureen Puettmann [1,*], Francesca Pierobon [2], Indroneil Ganguly [2], Hongmei Gu [3], Cindy Chen [4], Shaobo Liang [3], Susan Jones [5], Ian Maples [5] and Mark Wishnie [6]

[1] The Consortium for Research on Renewable Industrial Materials, Corvallis, OR 97330, USA
[2] College of the Environment, University of Washington, Seattle, WA 98105, USA; pierobon@uw.edu (F.P.); indro@uw.edu (I.G.)
[3] USDA Forest Service, Forest Products Laboratory, Madison, WI 53726, USA; Hongmei.gu@usda.gov (H.G.); sshliang@gmail.com (S.L.)
[4] Population Research Center, Portland State University, Portland, OR 97201, USA; cxc2@pdx.edu
[5] atelierjones LLC, Seattle, WA 98101, USA; Susan@atelierjones.com (S.J.); ian@atelierjones.com (I.M.)
[6] BTG Pactual Timberland Investment Group, Seattle, WA 98107, USA; mark.wishnie@btgpactual.com
* Correspondence: maureen@corrim.org; Tel.: +1-54-1231-2627

Abstract: Manufacturing of building materials and construction of buildings make up 11% of the global greenhouse gas emission by sector. Mass timber construction has the potential to reduce greenhouse gas emissions by moving wood into buildings with designs that have traditionally been dominated by steel and concrete. The environmental impacts of mass timber buildings were compared against those of functionally equivalent conventional buildings. Three pairs of buildings were designed for the Pacific Northwest, Northeast and Southeast regions in the United States to conform to mass timber building types with 8, 12, or 18 stories. Conventional buildings constructed with concrete and steel were designed for comparisons with the mass timber buildings. Over all regions and building heights, the mass timber buildings exhibited a reduction in the embodied carbon varying between 22% and 50% compared to the concrete buildings. Embodied carbon per unit of area increased with building height as the quantity of concrete, metals, and other nonrenewable materials increased. Total embodied energy to produce, transport, and construct A1–A5 materials was higher in all mass timber buildings compared to equivalent concrete. Further research is needed to predict the long-term carbon emissions and carbon mitigation potential of mass timber buildings to conventional building materials.

Keywords: mass timber; buildings; life cycle assessment; embodied carbon; embodied energy; Pacific Northwest; Northeast and Southeast

Citation: Puettmann, M.; Pierobon, F.; Ganguly, I.; Gu, H.; Chen, C.; Liang, S.; Jones, S.; Maples, I.; Wishnie, M. Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration. *Sustainability* **2021**, *13*, 13987. https://doi.org/10.3390/su132413987

Academic Editor: Adriana Del Borghi

Received: 15 November 2021
Accepted: 10 December 2021
Published: 18 December 2021

1. Introduction

Atmospheric carbon dioxide is the major contributor to global warming, making carbon emissions one of the world's most urgent environmental challenges. Recent research has indicated that afforestation can offer the single greatest opportunity for carbon mitigation [1–3]. However, delivering on this potential implies the afforestation of hundreds of millions of hectares in the next decade [4]. Forests have the ability to take up carbon dioxide and release oxygen back into the atmosphere through photosynthesis while storing carbon for decades or centuries in trees. For each metric ton (ton) of carbon stored in trees, 3.67 tons of carbon dioxide emission is removed. As forests age, their initially high carbon sequestration rates decrease, and eventually, carbon flux (i.e., sequestration and release) reaches a balance [3]. After disturbances, much of the stored carbon may be released back into the atmosphere relatively quickly via increased mortality, fire, or decomposition. Recent controversies about how forests best can offset carbon emissions have focused on the question of whether or not forests can increase their positive contribution to the carbon cycle if trees are harvested and the sequestered carbon is stored in long-term products, such as buildings [3,5–7].

Over the next decades, economies will grow because of an increase in population, resulting in a construction surge of buildings, bridges, and other structures. Particular attention has been given to the potential impact of mass timber (MT) penetration into these markets. Awareness of this comes from the expected increase in demand for wood products and the ability of forests to sustainably support the demand using carbon mitigation strategies, such as MT storing carbon in structures for decades. Mass timber is a defined category of engineered wood products (e.g., cross-laminated timber (CLT), glued laminated timber (glulam), mass plywood, and others) that enables the construction of tall buildings with wood [8–10]. Mass timber construction can have a greater carbon displacement benefit because it moves wood into building designs that traditionally have been dominated by steel and concrete materials.

Cross-laminated timber is at the forefront of the MT movement, enabling designers, engineers, and other stakeholders to build taller wood buildings. CLT panels are made by laminating dimension lumber orthogonally in alternating layers. Cross-laminated timber and other MT products store carbon and generate virtually no waste at a building site, as panels and beams are generally prefabricated before delivery.

Life-cycle assessment (LCA) has evolved as an internationally accepted method to objectively evaluate a product by identifying and quantifying energy and materials used and wastes released to the environment. Life-cycle assessment studies can evaluate full product life cycles, often referred to as "cradle-to-grave" or incorporate only a portion of the product's life cycle, referred to as "cradle-to-gate" or "gate-to-gate".

Life-cycle assessment studies of engineered timber products such as glued laminated timber (glulam) and CLT in construction have highlighted their environmental advantages over conventional materials such as concrete and steel [11–14]. However, no studies have yet compared the environmental impacts of MT buildings and conventional buildings for different building heights and across different United States (U.S.) regions. Cradle-to-gate product LCAs indicated net negative carbon emissions for MT products, which positions them with a high environmental advantage over nonwood materials [15–18].

The impacts that increased wood product utilization might have on forests and climate are complex. The current increase in wood demand from the MT movement is minimal. The maximum annual production capacity of North American MT manufacturers is 1.67 million m^3, consuming about 2.2% of the total softwood lumber production in North America [8]. However, because of the COVID pandemic, which put a lot of MT projects on hold, and the high cost of lumber in the U.S. relative to that in Europe and resulting increased imports of CLT, the softwood lumber usage in North American MT products was only 20% of the maximum capacity in 2020 [19].

The production of concrete and steel currently represents approximately 11% of annual global building greenhouse gas (GHG) emissions [20]. The global building stock, which primarily uses concrete and steel, is projected to double over the next 40 years, with most of that growth expected to occur in the southern hemisphere. To reduce the impact of this building expansion, MT buildings may offer a potentially appealing alternative to concrete and steel [11,21–29].

Whole-building LCA (WBLCA) studies have quantified and compared the environmental impact of MT buildings with that of traditional concrete and steel structures [11–13,21,22,25–28]. In one case study of midrise buildings [11], total carbon emissions for a five-story MT building were dominated by the manufacturing stage (77%), while the construction stage represented only 3% of the total carbon emissions. Total carbon emissions for the CLT building showed emissions of +1153 tons carbon dioxide equivalents (CO_2e) and storage of a total of −5315 tons of CO_2e, resulting in a net negative emission of −3847 tons CO_2e. Carbon emissions for an equivalent steel and concrete designs were +1372 tons CO_2e and +1718 tons CO_2e, respectively [11]. In summary, the CLT building produced 33% less carbon emission than the equivalent steel building and 16% less carbon emissions than the concrete.

In another case study on a midrise northwest building, the environmental benefits of using CLT in hybrid midrise structures compared to using concrete resulted in a 26.5% reduction in carbon emissions and an 8% reduction in nonrenewable fuels [25]. The hybrid CLT building stored −1556 tons of CO_2, offsetting the emissions from product manufacturing and construction and resulting in a net negative emission of −1222 tons of CO_2e.

Cross-laminated timber is a relatively new product, and research is ongoing to track how production changes and building designs result in lower embodied carbon than conventional materials and designs [12–14,25]. Clearly, CLT buildings have potentially greater benefits if efficient reprocessing at the end of building service life is implemented for reuse and recycle [3]. Increased benefits are also manifested when the timing of emissions is considered [12,27].

Building with wood provides an important climate change mitigation opportunity by storing carbon for decades and displacing emissions from nonrenewable materials together with reducing dependence on nonrenewable resources. Taking advantage of this opportunity requires sustainable forest management, which ensures that carbon sequestration is optimized in the forest while increasing carbon pools in harvested wood products for long-term storage [3,5,30–33] (Gu Johnston perez). This study is the first step in filling the knowledge gap on comparing functionally equivalent conventional buildings to those constructed using MT. The goal of this study was to determine the embodied carbon and energy contribution for three building heights, in three U.S. regions, using both conventional materials and MT products in the buildings' assemblies (structure, envelope, and interior walls).

2. Materials and Methods

Architectural Building Designs and Assumptions

The whole-building life-cycle assessment (WBLCA) was designed to compare MT buildings with functionally equivalent conventional concrete structures for their cradle-to-gate environmental impacts. A total of eighteen different modeling conditions were selected for the comparative building LCAs in the U.S., composed of three geographic locations: (1) the Pacific Northwest (PNW), (2) the Northeast (NE), and (3) the Southeast (SE). The building designs covered three building heights under the ICC TallWood Building Code, Type IV-A for 18-story buildings, Type IV-B for 12-story buildings, and Type IV-C for 8–9-story buildings (Supplementary Materials S1) (Table 1), and two building materials (MT and conventional concrete-and-steel) (Figure 1). It should be noted that all of these mid-and high-rise buildings were in fact hybrid buildings. The concrete buildings utilized both steel and concrete, just as the MT buildings utilized both concrete and steel for certain building elements as well as CLT and glulam. Other key assumptions (Supplementary Materials S1) included the different structural and constructability requirements for the PNW's seismic region (Supplementary Materials S1). All buildings were designed with mixed usage in mind. Floor-to-floor dimensions were 4.11 m for the commercial floors and 2.95 m for all residential floors. The basic building type was a simple rectangular shaped building with a central elevator and stair core with a floorplate of 25.91 m × 45.72 m (1185 m^2). For complete descriptions of the architectural plans and materials takeoffs for all building designs and regions, see Supplementary Materials S1.

Table 1. Mixed-use building program distribution for 8-, 12-, and 18-story buildings with mass timber or concrete designs constructed in the PNW, NE, and SE regions of the U.S.

	Stories	Floor Occupancy Ratio	Building Height	Total Floor Area
IBC 1/ for MT buildings		**Residential–Commercial**	**m**	**m²**
Type IV-C	8	6:2	26	9476
Type IV-B	12	8:4	48	14,214
Type IV-A	18	12:6	71	21,321 1/

1/ International Building Code (https://www.awc.org/pdf/education/des/AWC-DES607A-TallWood2021IBC-190619-color.pdf, accessed on 10 December 2021).

Figure 1. Examples of 8-, 12-, and 18-story PNW mass timber buildings with commercial floors and residential floors.

The buildings were not designed with any particular site in mind, except for their broad geographic regional differences. However, for some of the structural analysis, certain site assumptions had to be made given the need for appropriate soil analysis for soil pressure. Based on potential markets and production of MT the following three building sites were chosen for the WBLCA: (1) Seattle, Washington, (2) Boston, Massachusetts, and (3) Atlanta, Georgia.

Life-cycle inventory (LCI) datasets for the building materials used a combination of primary data [34] (CORRIM) and public databases [35–37] for the WBLCA modeling in this study. The study followed international standards for LCA methods and WBLCA analysis (ISO 14044, EN 15978, and ISO 21930) [38–40] as well as the building designs and assumptions in Supplementary Materials S1. Datasets and methodology were described further by Gu et al. [41]. The declared unit was 1 m^2 of the total floor area of the building. The system boundary for this assessment was cradle-to-gate and included modules A1—resource extraction, A2—transportation of materials to product manufacturing, A3—product manufacturing, A4—transportation of materials to construction site, and A5—construction energy use (Figure 2). Excluded from the study were modules B, C, and D [41].

Each region represents different energy mixes and timber species, and in the case of the PNW, additional seismic considerations drove differences in the building designs from those in the other two regions [41]. The species and MT production sites (actual and assumed) are listed in Table 2. For timber buildings, the density of the wood species influences the weight contribution of MT [12,41] (Table 3).

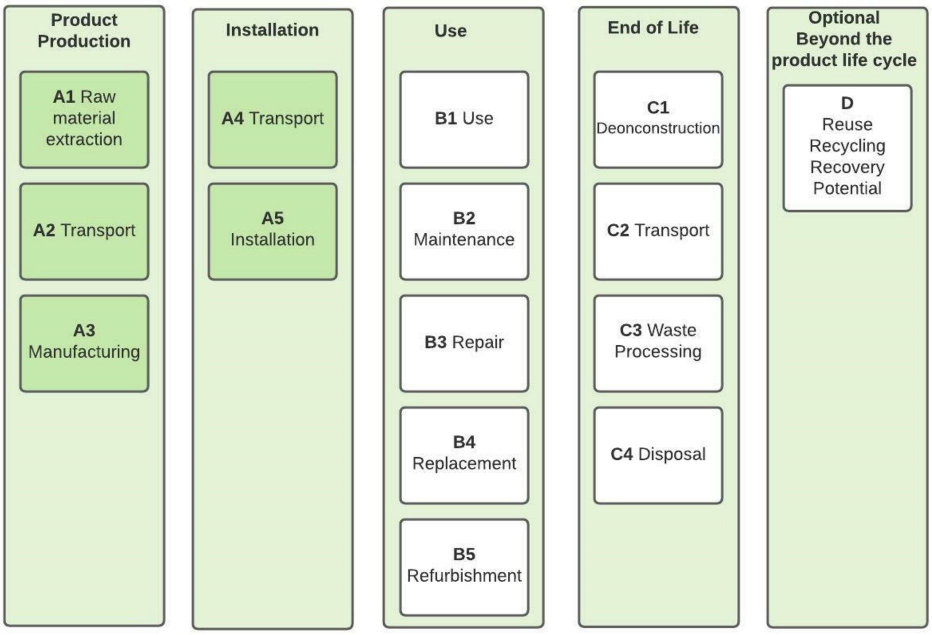


Figure 2. Life-cycle modules included in this study.

Table 2. Geographical regions, species, and mass timber production sites.

Geographic Regions	Species	CLT Production	Glulam Production
Pacific Northwest	Douglas fir and western hemlock	Spokane, Washington [2/]	Veneta, Oregon [2/]
Northeast	Eastern spruce and white pine	Lincoln, Maine	Lincoln, Maine
Southeast	Southern pine [1/]	Dothan, Alabama [2/]	Greenville, Alabama [2/]

[1/] Southern pines are a mixture of several species of longleaf (*Pinus palustris*), loblolly (*P. taeda*), short leaf (*P. chinate*), and slash (*P. elliottii*)) pines with similar characteristics. [2/] Actual production facilities for either CLT or glulam.

Fire protection of the MT structural elements was a critical factor in determining the allowable heights and uses for MT in mid- and high-rise buildings (Supplementary Materials S1). All MT building designs followed the new approved codes set by the International Code Council [42], which were adopted in the 2021 International Building Code. All MT elements in Type IV require some level of fire protection (Table 1). Type IV-A (up to 18 stories) requires noncombustible protection over all MT elements. Types IV-B and -C allow some exposure to MT [42]. The noncombustible material used in this study was either $\frac{1}{2}''$ gypsum or 5/8″ Type X gypsum sheathing (Supplementary Materials S2) [41].

Table 3. Wood density and species by region and global warming potential (GWP kg CO_2e for one cubic meter of lumber in the PNW, NE, and SE regions [43–45].

Region	Species	Wood Density [1/]	GWP
		kg/m^3	kg CO_2e/m^3
Pacific Northwest	Douglas fir and western hemlock	467	60.97
Northeast	Eastern spruce and white pine	434	46.78
Southeast	Southern pine	510	85.03

[1/] Wood only, input lamstock, oven-dry.

Reporting of embodied carbon was based on the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) evaluation method [46], and embodied energy was determined using the cumulative energy demand (CED). The building embodied carbon represents the total GHG emissions from cradle-to-gate of all the manufacturing of materials, transportation, and installation. Embodied energy is the sum of all energy consumed (renewable and nonrenewable) by all of the processes (including electricity use) associated with each building, from the mining and processing of natural resources to manufacturing, transport, product delivery, and construction. The WBLCA was modeled using the SimaPro LCA software [41,47] equipped with the USLCI [35], EcoInvent [36], and DATASMART 2019 [37] databases.

All materials used in buildings were assumed to be produced and sold domestically; therefore, only road and rail transportation modes were used. For distances shorter than 805 km (500 miles), the materials were assumed to be transported by truck, while for distances longer than 805 km, they were assumed to use a combination of truck and rail transport [41].

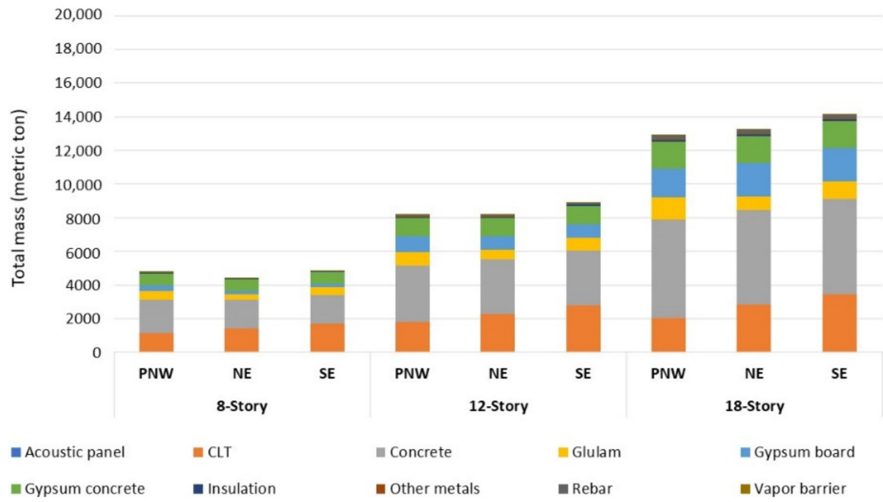
3. Results

The WBLCA results demonstrated the embodied carbon and embodied energy of using MT in mid- to high-rise buildings when compared to those of using conventional concrete. Highlights of the building differences in embodied carbon and energy demands by life cycle stage, regions, building height, materials, and assembly are presented in this paper. Since carbon emissions were the main focus of the study, global warming potential (GWP) expressed in carbon dioxide equivalents (CO_2e) is the main metric reported for embodied carbon and megajoules (MJ) for CED. Additional environmental impact indicators (smog, acidification, eutrophication, ozone waste, and fossil fuel depletion) are reported in Supplementary Materials S3 for all building heights and regions.

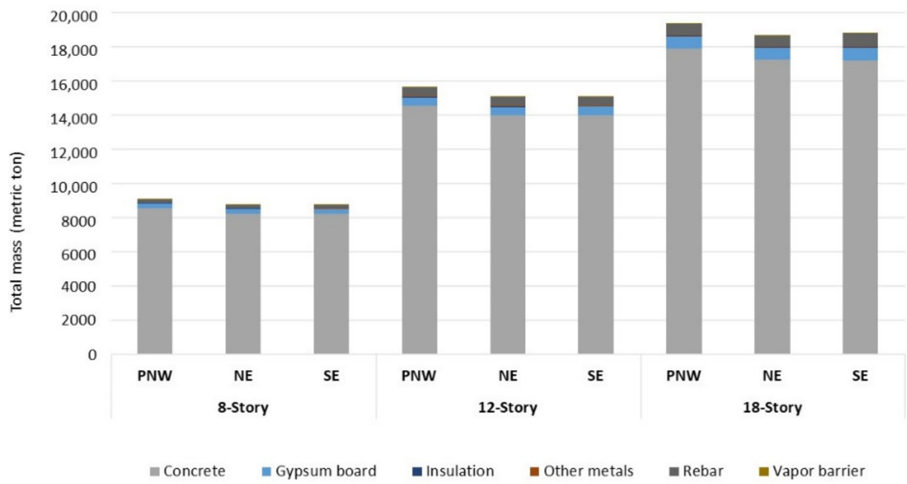
3.1. Building Mass

For both MT and concrete building designs, concrete represented the largest contribution by mass (Figure 3). In the MT building designs, concrete representation of total building mass was as low as 35% in the SE 8-story building and as high as 46% in the 18-story building in the PNW (Figure 3a). In the concrete building designs, concrete accounted for over 90% of the total mass of all the buildings (Figure 3b). The 8-story buildings had the largest contributions of CLT at 23%, 315, and 35% for the PNW, NE, and SE, respectively. Glulam contributed to under 10% in the 8-story buildings. Cross-laminated timber represented 22–31% of the mass for the 12-story buildings and 16–24% of the mass in the 18-story buildings. Glulam was below 10% of the mass in the 12-story and 6–10% in the 18-story buildings. Glulam had the highest representation in the PNW buildings, representing 10% of the mass in all building heights.

The mass contribution of MT was highest in the 8-story buildings and lowest in the 18-story buildings in all regions because the building code for taller buildings requires greater use of gypsum as an interior fire protectant. As a result of the strict fire codes, the 18-story building required over 11 times more gypsum than the 8-story MT design and over 2 times more gypsum than the 12-story MT design.



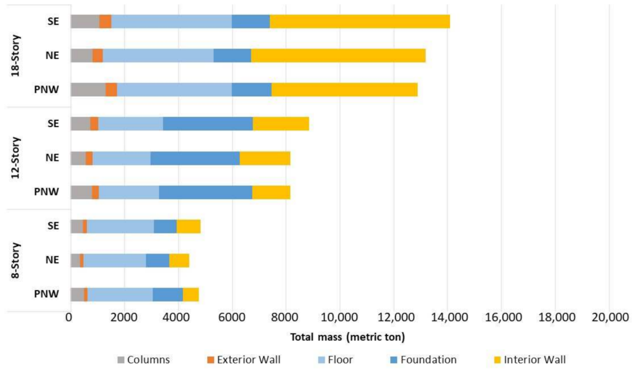
(**a**)



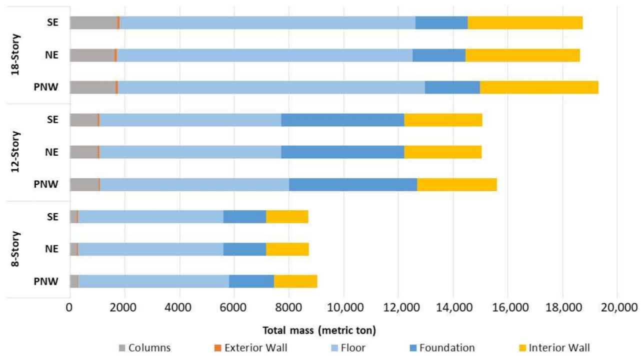
(**b**)

Figure 3. Mass of materials in 8-, 12-, and 18-story (**a**) mass timber and (**b**) concrete buildings in the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) United States.

Floors represented the largest mass contribution in the 8-story MT buildings, representing about half the total mass of these buildings, while the foundations had the highest mass contributions for the 12-story buildings, ranging from 38 to 42% depending on the region (Figure 4). In the 18-story buildings, the largest mass contribution was the interior wall assembly, which represented 42–52% of the MT whole-building mass. Gypsum wallboard represented about 29% of interior wall mass (Table 4), while for the whole building system, the gypsum wall contributed 14% to the total building mass, including the gypsum used in the exterior wall.



(**a**)



(**b**)

Figure 4. Mass of materials by building assembly (columns, exterior walls, floors, foundation, interior walls) for 8-, 12-, and 18-story buildings from the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) United States for (**a**) mass timber buildings and (**b**) concrete buildings.

Table 4. Material contribution of the interior wall assembly for mass timber 18-story buildings from the Pacific Northwest, Northeast, and Southeast United States.

Material Used the Interior Walls	Mass of Materials kg/m^2 of Floor Area	Composition by Mass	Contribution to Embodied Carbon
	Pacific Northwest		
Concrete	165.4	65.0%	32.8%
CLT	0.0	0.0%	0.0%
Gypsum wall board	75.3	29.6%	31.5%
Insulation	1.5	0.6%	5.7%
Other metals	2.9	1.1%	10.6%
Rebar	9.5	3.7%	19.4%
	Northeast		
Concrete	145.3	52.3%	32.9%
CLT	39.4	14.2%	11.0%
Gypsum wall board	81.6	29.4%	32.7%
Insulation	1.8	0.6%	3.3%
Other metals	0.8	0.3%	3.1%
Rebar	8.7	3.1%	17.0%
	Southeast		
Concrete	158.7	50.7%	30.2%
CLT	53.0	16.9%	17.3%
Gypsum wall board	89.3	28.5%	30.1%
Insulation	1.9	0.6%	3.1%
Other metals	0.9	0.3%	3.0%
Rebar	9.5	3.0%	16.3%

3.2. Embodied Carbon

Over all regions and building heights, the MT buildings held lower embodied carbon than their functionally equivalent concrete buildings (Figure 5). In general, embodied carbon per unit of area increased with building height in MT buildings as the quantity of concrete, metals, and other nonrenewable materials increased. The NE MT buildings had the largest reduction in embodied carbon compared to the corresponding concrete buildings, with the SE MT buildings showing the smallest reduction, because of the regional electricity grid, wood species, and transportation differences. Across all the building heights and regions, MT buildings exhibited reductions in embodied carbon varying between 22% and 50% compared to the corresponding concrete buildings (Figure 5).

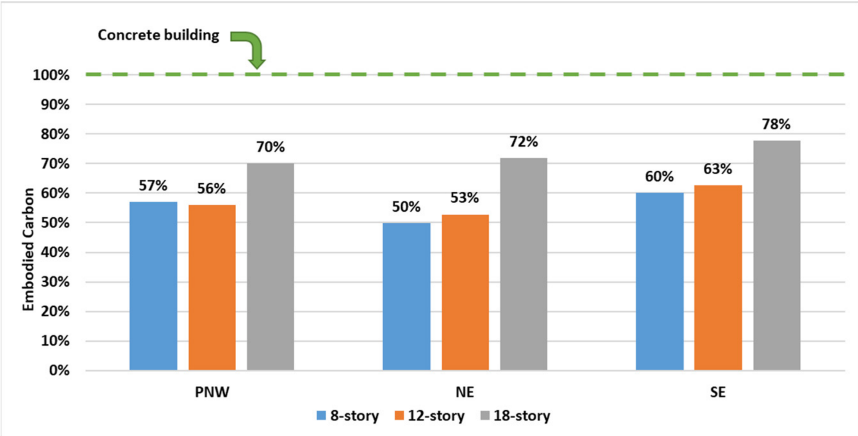


Figure 5. Embodied carbon (relative basis) of mass timber buildings compared to the corresponding concrete buildings of 8, 12, and 18 stories in the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) United States.

The results of the whole-building embodied carbon analysis are shown in Figure 6. The PNW concrete 12-story buildings had the highest embodied carbon per unit area of all building designs and regions (Figure 6b). This was attributed to the components needed to meet the PNW building code requirements for seismic protection, as well as the mat footing foundation design used only for the 12-story buildings (Supplementary Materials S1). The equivalent 12-story MT building in the PNW had a 44% reduction in embodied carbon. The largest reductions in embodied carbon were in all 8-story MT buildings, for which the results showed reductions of 40–50% compared to the equivalent concrete buildings (Figures 5 and 6).

Embodied carbon of the MT buildings was greatest in the A1–A3 life cycle stages, which represented 85–91% of the carbon emissions. Transportation (A4) accounted for 5–11% and construction (A5) for 3–4% (Table 5). For concrete designs, the A1–A3 life cycle stage represented 94–96% of the carbon emissions. The biggest difference was in the A4 modules. For concrete buildings, the A4-transportation accounted for about 2%, 1%, and 0.5% of carbon emissions in the PNW, NE, and SE, respectively.

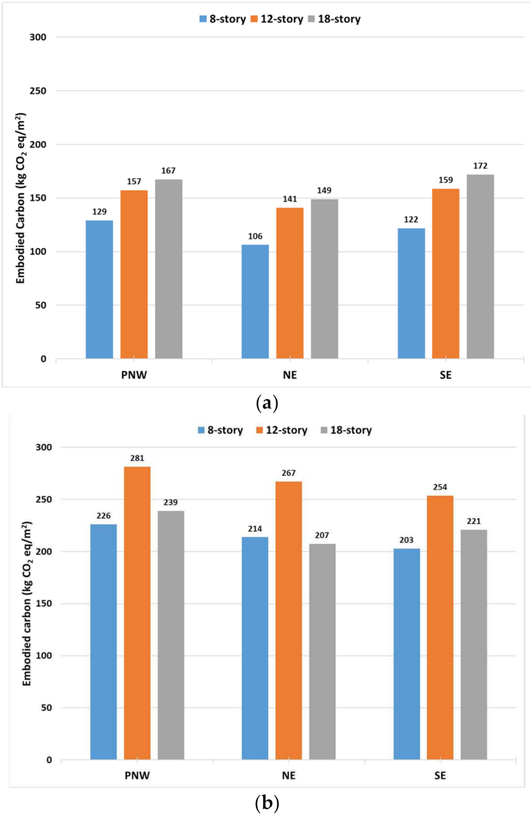
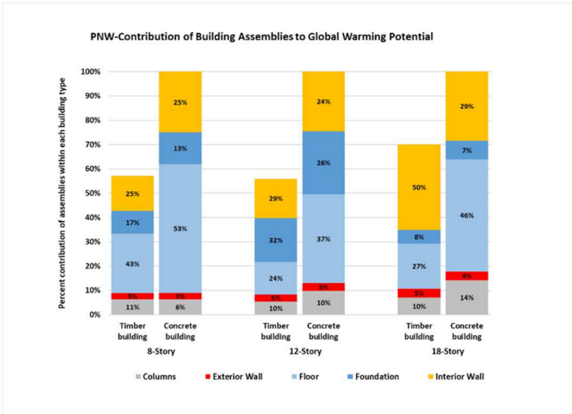


Figure 6. Embodied carbon of 8-, 12-, and 18-story (**a**) mass timber and (**b**) concrete buildings in the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) United States.

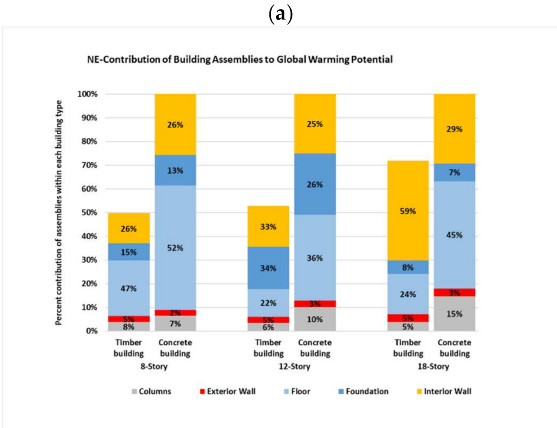
Table 5. Total embodied carbon by life cycle stage (A1–A5) for all mass timber and concrete building designs.

PNW Embodied Carbon kg CO_2e/m^2									
Building System		**A1–A3**		**A4**		**A5**		**Total**	
8-story	Mass timber building	113.4	87.9%	11.6	9.0%	4.0	3.1%	129.1	100.0%
	Concrete building	212.5	94.0%	5.5	2.5%	8.0	3.5%	226.0	100.0%
12-story	Mass timber building	139.2	88.5%	12.8	8.1%	5.3	3.4%	157.3	100.0%
	Concrete building	264.5	94.0%	6.3	2.2%	10.7	3.8%	281.4	100.0%
18-story	Mass timber building	146.1	87.3%	14.8	8.8%	6.5	3.9%	167.3	100.0%
	Concrete building	223.4	93.5%	5.3	2.2%	10.1	4.2%	238.9	100.0%
NE Embodied Carbon kg CO_2e/m^2									
		A1–A3		**A4**		**A5**		**Total**	
8-story	Mass timber building	90.7	85.2%	12.0	11.2%	3.7	3.5%	106.3	100.0%
	Concrete building	203.7	95.3%	2.7	1.3%	7.4	3.5%	213.8	100.0%
12-story	Mass timber building	121.4	86.1%	14.2	10.1%	5.3	3.8%	141.0	100.0%
	Concrete building	254.0	95.1%	3.1	1.2%	9.9	3.7%	267.0	100.0%
18-story	Mass timber building	130.0	87.2%	13.0	8.7%	6.1	4.1%	149.1	100.0%
	Concrete building	196.3	94.6%	2.6	1.2%	8.6	4.1%	207.4	100.0%
SE Embodied Carbon kg CO_2e/m^2									
		A1–A3		**A4**		**A5**		**Total**	
8-story	Mass timber building	110.0	90.4%	7.62	6.3%	4.09	3.4%	121.7	100.0%
	Concrete building	194.5	95.9%	0.96	0.5%	7.37	3.6%	202.8	100.0%
12-story	Mass timber building	144.0	90.8%	8.76	5.5%	5.81	3.7%	158.6	100.0%
	Concrete building	242.6	95.7%	1.12	0.4%	9.86	3.9%	253.5	100.0%
18-story	Mass timber building	157.2	91.4%	7.68	4.5%	7.09	4.1%	172.0	100.0%
	Concrete building	210.5	95.3%	0.96	0.4%	9.43	4.3%	220.9	100.0%

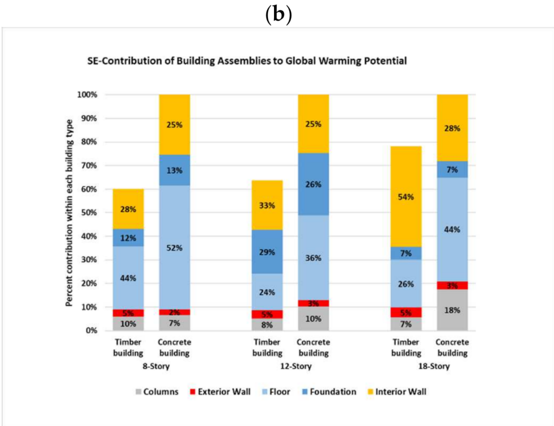
In the 18-story MT buildings, the interior wall represented 50–59% of the total embodied carbon impact of the whole building depending on the region (Figure 7). Gypsum wall board was used in both interior and exterior wall systems. Within the interior wall assembly of the 18-story MT buildings, gypsum wall board represented about 29–30% of the interior wall mass and 30–33% of the embodied carbon depending on the region (Table 4). For the 18-story MT building systems in all regions, gypsum wall board contributed 13–15% of the mass (Figure 3a) and 16–21% of the total embodied carbon (Figure 8), while the two MT structure components (CLT and glulam) contributed 28–39% and concrete (including gypsum–concrete) 30–35% of the whole-building embodied carbon. This included the gypsum in the exterior wall.



(**a**)

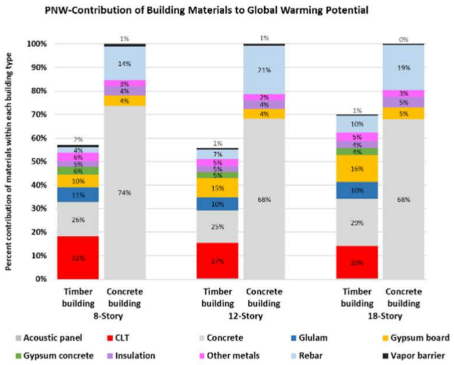


(**b**)

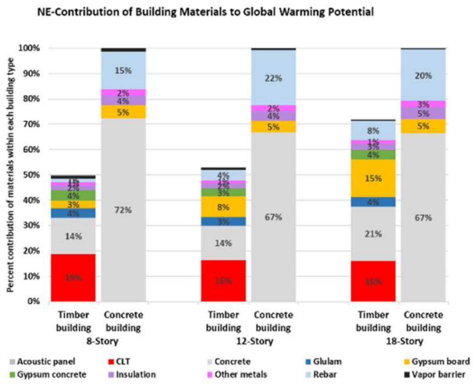


(**c**)

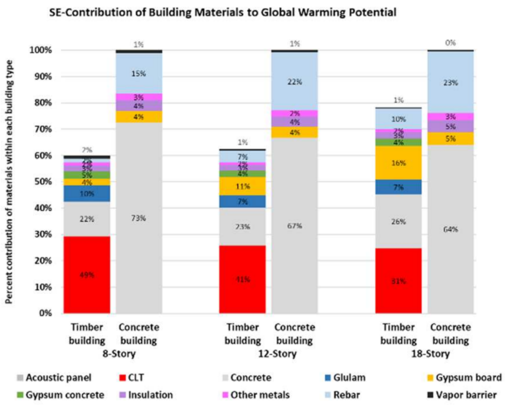
Figure 7. Contribution of building assemblies to total embodied carbon of 8-, 12-buildings in the (**a**) Pacific Northwest (PNW), (**b**) Northeast (NE), and (**c**) Southeast (SE) United States.



(**a**)



(**b**)



(**c**)

Figure 8. Contribution of building materials to total embodied carbon of 8-, 12-, and 18-story buildings in the (**a**) Pacific Northwest (PNW), (**b**) Northeast (NE) and (**c**) Southeast (SE) US.

3.3. Energy Use

Both renewable and nonrenewable energy were consumed during extraction, production, transport, and manufacture of the materials used in all building designs. In all building designs, total embodied energy was higher for the MT buildings compared to the equivalent concrete buildings (Table 6), independently of the region.

Table 6. Cradle-to-gate embodied energy (absolute basis and relative basis) for 8-, 12-, and 18-story mass timber and concrete building designs in the PNW, NE, and SE regions.

PNW Embodied Energy MJ/m²										
		A1–A3		**A4**		**A5**		**Total**		**Total**
Building Design		**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Energy**
8-story	Mass timber	1145	1526	0	148	0	55	1146	1729	2875
	Concrete	62	1857	0	71	0	109	62	2037	2099
12-story	Mass timber	1217	1852	0	163	0	73	1217	2088	3305
	Concrete	78	2405	0	80	0	146	78	2631	2709
18-story	Mass timber	1090	1892	0	188	0	89	1091	2169	3260
	Concrete	67	2016	0	68	0	139	67	2222	2289
NE Embodied Energy MJ/m²										
8-story	Mass timber	799	1448	0	152	0	51	800	1651	2451
	Concrete	57	1816	0	34	0	101	58	1952	2010
12-story	Mass Timber	875	1878	0	181	0	73	875	2132	3007
	Concrete	72	2355	0	40	0	135	72	2530	2602
18-story	Mass timber	698	1829	0	165	0	83	698	2077	2775
	Concrete	56	1806	0	32	0	118	56	1956	2012
SE Embodied Energy MJ/m²										
8-story	Mass timber	869	1489	0	98	0	56	869	1643	2512
	Concrete	53	1735	0	12	0	101	53	1848	1901
12-story	Mass timber	952	1917	0	113	0	79	952	2109	3061
	Concrete	63	2236	0	14	0	135	64	2385	2449
18-story	Mass timber	827	1991	0	99	0	97	827	2186	3014
	Concrete	55	1962	0	12	0	129	55	2104	2158
PNW Embodied Energy, Relative Basis										
		A1–A3		**A4**		**A5**		**Total**		**Total**
Building Design		**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Renewable**	**Nonrenewable**	**Energy**
8-story	Mass timber	39.83%	53.08%	0.01%	5.13%	0.00%	1.92%	39.86%	60.14%	100%
	Concrete	2.95%	88.47%	0.01%	3.37%	0.01%	5.18%	2.95%	97.05%	100%
12-story	Mass Timber	36.82%	56.04%	0.01%	4.93%	0.00%	2.21%	36.82%	63.18%	100%
	Concrete	2.88%	88.78%	0.01%	2.95%	0.01%	5.39%	2.88%	97.12%	100%
18-story	Mass Timber	33.44%	58.04%	0.01%	5.77%	0.01%	2.73%	33.47%	66.53%	100%
	Concrete	2.93%	88.07%	0.01%	2.97%	0.01%	6.07%	2.93%	97.07%	100%
NE Embodied Energy, Relative basis										
8-story	Mass timber	32.60%	59.08%	0.01%	6.19%	0.00%	2.09%	32.64%	67.36%	100%
	Concrete	2.84%	90.35%	0.00%	1.71%	0.01%	5.04%	2.89%	97.11%	100%
12-story	Mass Timber	29.10%	62.45%	0.01%	6.01%	0.01%	2.44%	29.10%	70.90%	100%
	Concrete	2.77%	90.51%	0.00%	1.53%	0.01%	5.19%	2.77%	97.23%	100%
18-story	Mass Timber	25.15%	65.91%	0.01%	5.95%	0.01%	3.00%	25.15%	74.85%	100%
	Concrete	2.78%	89.76%	0.00%	1.61%	0.01%	5.84%	2.78%	97.22%	100%
SE Embodied Energy, Relative basis										
8-story	Mass timber	34.59%	59.28%	0.00%	3.91%	0.00%	2.23%	34.59%	65.41%	100%
	Concrete	2.79%	91.27%	0.00%	0.65%	0.01%	5.30%	2.79%	97.21%	100%
12-story	Mass timber	31.10%	62.63%	0.00%	3.68%	0.01%	2.60%	31.10%	68.90%	100%
	Concrete	2.57%	91.30%	0.00%	0.59%	0.01%	5.51%	2.61%	97.39%	100%
18-story	Mass Timber	27.44%	66.06%	0.00%	3.28%	0.01%	3.22%	27.44%	72.56%	100%
	Concrete	2.55%	90.90%	0.00%	0.58%	0.01%	5.98%	2.55%	97.45%	100%

Total (A1–A5) nonrenewable energy (fossil and nuclear) was lower in the MT than in the concrete designs for the 8- and 12-story buildings (Table 6), while the 18-story MT buildings (NE and SE regions) consumed more nonrenewable fuels than the equivalent concrete designs. This higher nonrenewable fuel consumption in these two regions and not the PNW was primarily from electricity use for regional production of building components (e.g., CLT and glulam). The PNW regional grids use a higher percentage of renewable fuels.

The transportation distances of the CLT and glulam from the manufacturers to the building site over all regions ranged from 332 to 490 km [41]. The transportation of MT components was the driver in the A4 stage. Transportation (A4) from production to construction accounted for 5–8% of nonrenewable energy use for MT buildings and 1–3% for concrete buildings. Construction (A5) energy used only diesel fuel and accounted for 3–5% on the nonrenewable fuel use for MT buildings and 5–6% for concrete buildings.

Renewable energy use originated mainly from the production of the lumber that was the feedstock for both CLT and glulam. For MT, most of the renewable energy was generated by combustion of biomass such as bark, sawdust, chips, and other waste generated during the milling processes [43–45]. The total renewable energy used, from A1–A5, in the MT buildings represented 25–40% of the total energy, depending on the region and building height (Table 6). The percentage of renewable energy decreased with height; it represented 33–40% in the 8-story buildings and 25–33% in the 18-story buildings, wherein there was greater use of on nonrenewable materials such as gypsum.

4. Discussion

4.1. Embodied Carbon (A1–A5)

Mass timber buildings had lower overall embodied carbon than equivalent concrete buildings within the cradle-to-construction gate system boundary. There were also differences in regional buildings' embodied carbon discovered in this study, which could be attributed to differences in electricity grids, the distance of transporting materials, and wood species. In addition, the upstream impacts of producing the softwood lumber used to make CLT and glulam were transferred downstream with the lumber inputs for the production of MT [43–45]. Most of the regional differences came from softwood lumber, which was primarily a result of species density, green moisture content, and type of energy used for drying the lumber with different kiln-drying schedules. These upstream impacts were seen in the overall results in MT buildings over the three regions.

While MT buildings produce carbon emissions during their production and installation, MT buildings also offset their carbon emissions by storing carbon for the time of building is in use (Figure 9). In all three MT designs in all regions, more carbon was stored in the building than was released during production and installation (Figure 9), with results similar to those of earlier published studies [11,13,14,25] in which net carbon (storage minus emission) ranged from −1222 to −5315 tons CO_2e [11,25] for the whole buildings. By life-cycle stage, 88–90% of the embodied carbon was generated during A1–A3 (extraction through manufacturing), 6–11% during product transportation (A4) and 3–4% during construction (A5). Salazar and Puettmann [11] reported 87%, 8%, and 5% for A1–A3, A4, and A5, respectively, results comparable to this study. Current standards on the reporting of embodied carbon (global warming potential) do not include biogenic carbon emissions released from the combustion of renewable fuels as emissions under sustainable forestry practices.

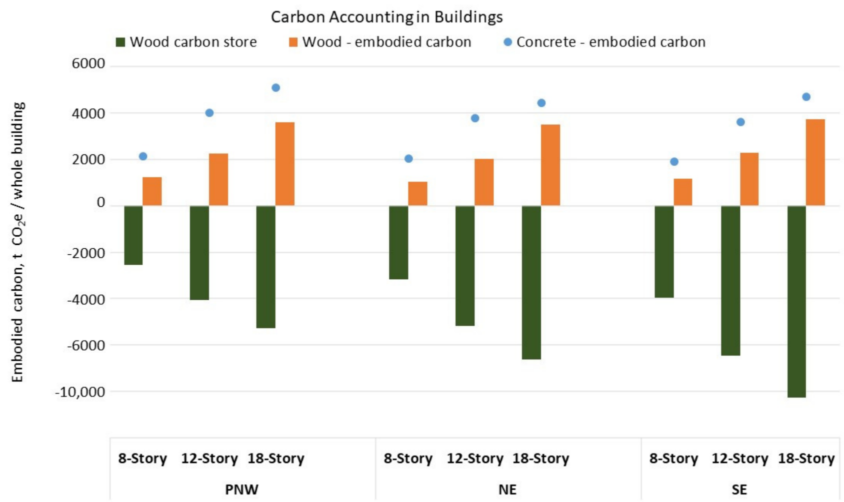


Figure 9. Cradle-to-gate (A1–A5) carbon accounting of MT buildings and embodied carbon of concrete buildings (blue dot).

4.2. Embodied Carbon—Assemblies

In MT and concrete 12-story buildings in all three regions, the foundation had the highest embodied carbon contribution. This was due to the mat footing design for the 12-story MT buildings. This required more cement and rebars than the spread footing design for the 8-story buildings and the pile foundation design for the 18-story buildings (Supplementary Materials S2) [41].

Following the requisite code performances as required under the new building codes for mass timber buildings (Supplementary Materials S1), there was additional consideration given to the fire and life safety code requirements. Interior walls represented the largest contribution to embodied carbon for the 18-story buildings because of strict fire codes requiring nearly 11 times more gypsum than for the 8-story buildings and 2 times more gypsum than for the 12-story buildings. Gypsum wall board was assumed as the requisite noncombustible protection and was required only for the MT assemblies and not for the equivalent noncombustible concrete assemblies [41] (Supplementary Materials S1 and S2).

4.3. Embodied Energy

All MT buildings used more energy to produce than the equivalent concrete buildings. As mentioned earlier, the energy requirement to produce lumber was transferred to MT production and again to the whole-building cradle-to-gate energy use. Energy consumption was not directly in line with embodied carbon, and energy content of the fuels used was not equal. Wood fuels have a lower heating value than fossil fuels. Recently produced life-cycle assessment reports [43,44] on the production of softwood lumber in the United States showed that nearly 100% of the energy was from renewable biomass, mostly generated at the facilities. When these burdens were transferred with the quantity of MT used in the whole buildings along with all the materials used in the buildings, the use of renewable energy ranged from 33–40% in the 8-story buildings, to 25–33% in the 12-story buildings, to 27–35% in the 18-story buildings. Over all regions, 88–91% of nonrenewable fuels used in the MT designs were from modules A1–A3. In the concrete buildings, the maximum amount of renewable energy use was only 3%.

Transportation of MT to construction sites (A4) had minimal impact on the total whole-building energy use (5–8%). On the other hand, concrete transportation to the construction site was limited to only 1–3% of the buildings' total nonrenewable energy. This was due to the short local transport of concrete and the fact that CLT is a customized product and is more difficult to be sourced locally. Current regional production facilities for MT are limited to either one or none in certain regions, making transportation distances longer. Our assumptions were based on having only one CLT and glulam facility within each region. Distances ranged from 354 to 473 km for CLT and 332 to 490 km for glulam [41]. Concrete transport distances were short, limited to under 52 km to the construction site.

As an example of the potential impact of A4, when the transportation distance for CLT and glulam was doubled for the 8-story MT building, the A4 energy use contribution increased to 15% for the whole building. We mention this because some of the current whole-building design embodied carbon models available use environmental product declarations that might not include the A4 module in the total embodied carbon of the product. Therefore, preferred purchasing based solely on A1–A3 embodied carbon could have unintended consequences on the overall embodied carbon of MT buildings.

5. Conclusions

Manufacturing of all building materials and construction of buildings consume energy and emit carbon. Sustainable use of wood products gives the opportunity for reducing global greenhouse gas emissions by: (1) growing more trees; (2) managing forests sustainably for yield; (3) using local wood sources and products to reduce transportation impacts; (4) producing wood products used in long-term service; (5) building for deconstruction with reuse and recycling potential of all wood elements; (6) replacing fossil-based, energy-intensive materials with wood products in low-, mid-, and high-rise buildings; and (7) using wood residues for energy generation during wood product manufacturing which displaces fossil carbon emissions.

This study demonstrated embodied carbon (global warming potential) reductions when replacing concrete and steel with MT in all three levels of building, 8, 12, and 18 stories, in all three U.S. regions studied. Reductions of 22% to 50% in carbon emissions were achieved compared to the functionally equivalent concrete buildings based on cradle-to-construction gate assessment. Regional differences in the embodied carbon of buildings were due to the regional building code requirements for MT building designs, MT feedstock production differences, and regional electricity grid differences. Mass timber products, if sourced from local forest resources and produced locally, can keep the whole-building embodied carbon impacts lower and avoid unintended consequences as a result of long transportations.

This study clearly showed the potential of carbon emission reductions that could be achieved in MT construction compared to the construction of traditional concrete mid- to high-rise buildings. However, it also indicated the need for updates and improvements in research and testing so that building codes and materials use can reflect actual risk, as we showed with the impact of gypsum wall board on the 18-story buildings.

A plethora of data exist on the favorable environmental performance of wood as a building material and its role in carbon mitigation. The opportunities for improvement in the use of wood as a building material are endless, including improving material and building designs, innovative products, building codes that allow the use of MT for high-rise buildings and displace fossil-intensive alternatives, and better communication and education on how to improve the efficiency of wood use and avoid unintended consequences.

Supplementary Materials: The following are available online https://www.mdpi.com/article/10.3390/su132413987/s1. Figure S1. Building designs in three regions of the United States—Pacific Northwest, Northeast, and Southeast. Figure S2. Required noncombustible protection on mass timber elements by construction type (source: https://www.woodworks.org/wp-content/uploads/wood_solution_paper-TALL-WOOD.pdf) (accessed on 14 December 2014). Figure S3. Foundation types for (a) 8-story, (b) 12-story, and (c) 18-story mass timber buildings. Table S1. Foundation approach for each building design for all regions. Table S2. Glazing and opaque percent of wall area for 8-, 12-, and 18-story buildings for all regions. Table S3. Resulting mixed use building program distribution for 8-, 12-, and 18-story buildings. Table S4. Whole-building bill of materials, PNW. Table S5 Whole-building bill of materials, NE. Table S6. Whole-building bill of materials, SE. Table S7. Cradle-to-gate (A1–A5) life cycle impacts of mass timber and concrete buildings from the Pacific Northwest (PNW), Northeast (NE), and Southeast (SE) United States.

Author Contributions: Conceptualization, M.P., F.P., I.G., M.W., C.C., H.G., S.J., I.M. and S.L.; methodology, M.P., F.P., I.G., C.C., H.G., S.J., I.M. and S.L.; software, M.P., F.P., C.C. and S.L., validation, M.P., F.P., C.C., H.G., I.M. and S.L.; formal analysis, M.P., F.P., C.C., S.L. and H.G; investigation, M.P., F.P., C.C., S.L. and H.G.; data curation, M.P., F.P., C.C., I.M. and S.L.; writing—original draft preparation, M.P.; writing—review and editing, M.P., F.P., H.G. and I.G; supervision, M.P., I.G., M.W. and H.G.; project administration, M.W.; funding acquisition, M.W. All authors have read and agreed to the published version of the manuscript.

Funding: External funding was received by the Nature Conservancy.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This article makes up part of a larger five-phased project that was initiated by the Nature Conservancy (nature.org) through generous support from the Climate and Land Use Alliance and the Doris Duke Charitable Foundation (DDCF). The work on which this project was based was also funded in whole or in part through a cooperative agreement with the USDA Forest Service, Forest Products Laboratory, Forest Products Marketing Unit (17-CA-11111169-031) *. The Nature Conservancy initiated this project to further the collective understanding of the potential benefits and risks of increasing demand for forest products. The Conservancy is focused on delivering critical safeguard frameworks to mitigate any potential risks to forest ecosystems as mass timber demand increases. * In accordance with Federal Law and U.S. Department of Agriculture policy, this institution is prohibited from discriminating on the basis of race, color, national origin, sex, age, or disability. (Not all prohibited bases apply to all programs.) To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, Room 326-W, Whitten Building, 1400 Independence Avenue, SW, Washington, DC 20250-9410, or call (202) 720-5964 (voice and TDD). USDA is an equal opportunity provider, employer, and lender.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Bastin, J.-F.; Finegold, Y.; Garcia, C.; Mollicone, D.; Rezende, M.; Routh, D.; Zohner, C.M.; Crowther, T.W. The global tree restoration potential. *Science* **2019**, *365*, 76–79. [CrossRef]
2. Griscom, B.W.; Adams, J.; Ellis, P.W.; Houghton, R.A.; Lomax, G.; Miteva, D.A.; Schlesinger, W.H.; Shoch, D.; Siikamäki, J.V.; Smith, P.; et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11645–11650. [CrossRef]
3. Lippke, B.; Puettmann, M.; Oneil, E.; Oliver, C.D. The plant a trillion trees campaign to reduce global warming—Fleshing out the concept. *J. Sustain. For.* **2021**, *40*, 1–31. [CrossRef]
4. Food and Agriculture Organization of the United Nations (FAO). *FAO Statistics Division (FAOSTAT)*; FOA: Rome, Italy, 2015. Available online: https://www.fao.org/faostat/en/#home (accessed on 15 December 2021).
5. Ganguly, I.; Pierobon, F.; Sonne Hall, E. Global warming mitigating role of wood products from Washington State's private forests. *Forests* **2020**, *11*, 194. [CrossRef]
6. Hudiburg, T.W.; Law, B.E.; Moomaw, W.R.; Harmon, M.E.; Stenzel, J.E. Meeting GHG reduction targets requires accounting for all forest sector emissions. *Environ. Res. Lett.* **2019**, *14*, 095005. [CrossRef]
7. Stewart, W.C.; Nakamura, G.M. Documenting the full climate benefits of harvested wood products in Northern California: Linking harvests to the US greenhouse gas inventory. *For. Prod. J.* **2012**, *62*, 340–353. [CrossRef]
8. Anderson, R.; Atkins, D.; Beck, B.; Dawson, E.; Gayle, C. *State of the Industry North American Mass Timber*; Self-Publishing Services LLC: Missoula, MT, USA, 2020; p. 156.
9. Bengston, D.N. The Revolutionary Role of Wood in Our Future. 2021. Available online: https://www.usda.gov/media/blog/2018/01/05/revolutionary-role-wood-our-future (accessed on 15 December 2021).
10. Zelinka, S.L.; Williamson, T.; Martinson, K.L.; Ritter, M.A. Research needs assessment for the mass timber industry. In Proceedings of the 2nd North American Mass Timber Research Needs Workshop, Madison, WI, USA, 13–14 November 2018.
11. Salazar, J.; Puettmann, M.E. *Whole-Building LCA Case Study of a Mid-Rise Office Building in New England*; Unpublished Work; New England Forestry Foundations: Littleton, MA, USA, 2019; p. 58.
12. Chen, C.X.; Pierobon, F.; Ganguly, I. Life cycle assessment (LCA) of cross-laminated timber (CLT) produced in western Washington: The role of logistics and wood species mix. *Sustainability* **2019**, *11*, 1278. [CrossRef]
13. Chen, Z.; Gu, H.; Bergman, R.; Liang, S. Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the Athena Impact Estimator for buildings. *Sustainability* **2020**, *12*, 4708. [CrossRef]

14. Liang, S.; Gu, H.; Bergman, R.; Kelley, S. Comparative life-cycle assessment of a mass timber building and concrete alternative. *Wood Fiber Sci.* **2020**, *52*, 217–229. [CrossRef]
15. ASTM. Freres Lumber Environmental Product Declaration Mass Ply Panels. 2020. Available online: https://www.astm.org/CERTIFICATION/DOCS/563.EPD_For_FinalFreres_Lumber_Company.pdf (accessed on 5 October 2021).
16. ASTM. Structurlam Mass Timber Environmental Product Declaration. 2020. Available online: https://www.astm.org/CERTIFICATION/DOCS/480.EPD_FOR_Structurlam_CLT_20200113.pdf (accessed on 5 October 2021).
17. Puettmann, M.E.; Sinha, A.; Ganguly, I. Life cycle energy and environmental impacts of cross laminated timber made with coastal Douglas-fir. *J. Green Build.* **2020**, *14*, 17–33. [CrossRef]
18. Bowers, T.; Puettmann, M.E.; Ganguly, I.; Eastin, I. Cradle-to-gate life-cycle impact analysis of glued-laminated (glulam) timber: Environmental impacts from glulam produced in the US Pacific Northwest and southeast. *For. Prod. J.* **2017**, *17*, 368–380. [CrossRef]
19. Anderson, R. (The Beck Group, Portland, OR, USA). Personal communication, 2021.
20. United Nations Environment Programme. Emissions Gap Report 2020. 2020. Available online: www.unenvironment.org/emissionsgap (accessed on 15 December 2021).
21. Buchanan, A.H.; John, S.; Love, S. LCA and carbon footprint of multi-story timber buildings compared with steel and concrete buildings. *N. Z. J. For.* **2013**, *54*, 9–18.
22. Milaj, K.; Sinha, A.; Miller, T.H.; Tokarczyk, J.S. Environmental utility of wood substitution in commercial buildings using life-cycle analysis. *Wood Fiber Sci.* **2017**, *49*, 338–358.
23. Meil, J.; Lippke, B.; Perez-Garcia, J.; Bowyer, J.; Wilson, J. *Environmental Impacts of a Single Family Building Shell—From Harvest to Construction*; CORRIM: Corvallis, OR, USA, 2004; p. 44.
24. Perez-Garcia, J.; Lippke, B.; Briggs, D.; Wilson, J.B.; Bowyer, J.; Meil, J. The environmental performance of renewable building materials in the context of residential construction. *Wood Fiber Sci.* **2005**, *37*, 3–17.
25. Pierobon, F.; Huang, M.; Simonen, K.; Ganguly, I. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA comparative case study in the US PNW. *J. Build. Eng.* **2019**, *26*, 100862. [CrossRef]
26. Robertson, A.B.; Lam, F.C.F.; Cole, R.J. A comparative cradle-to-gate lifecycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete. *Buildings* **2012**, *2*, 245–270. [CrossRef]
27. Liang, S.; Gu, H.; Bergman, R. Environmental life-cycle assessment and life-cycle cost analysis of a high-rise mass timber building: A case study in Pacific Northwestern United States. *Sustainability* **2021**, *13*, 7831. [CrossRef]
28. Forterra. Mass Timber: The Innovative Future of Our Built Environment. 2018. Available online: https://forterra.org/editorial/mass-timber (accessed on 11 August 2021).
29. Upton, B.; Miner, R.; Spinney, M.; Heath, L.S. The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. *Biomass Bioenergy* **2008**, *32*, 1–10. [CrossRef]
30. Schmidt, J.; Griffin, C.T. Barriers to the design and use of cross-laminated timber structures in high-rise multi-family housing in the United States. In *Structures and Architecture*, 1st ed.; Cruz, P.J., Ed.; CRC Press: Boca Raton, FL, USA, 2013; pp. 2225–2231.
31. Gu, H.; Nepal, P.; Arvanitis, M.; Alderman, D. Carbon impacts of engineered wood products in construction. In *Engineered Wood Products for Construction*; InTech Open: London, UK, 2021.
32. Johnston, C.M.T.; Radeloff, V.C. Global mitigation potential of carbon stored in harvested wood products. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 14526–14531. [CrossRef]
33. Perez-Garcia, J.; Lippke, B.; Comnick, J.; Manriquez, C. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fiber Sci.* **2005**, *37*, 140–148.
34. The Consortium for Research on Renewable Industrial Materials. Available online: www.corrim.org (accessed on 10 August 2021).
35. National Renewable Energy Laboratory. *U.S. Life Cycle Inventory Database*. Available online: http://www.nrel.gov/lci/LTS (accessed on 11 August 2021).
36. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (Part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
37. LTS. DataSmart. Available online: https://ltsexperts.com/services/software/datasmart-life-cycle-inventory (accessed on 5 October 2021).
38. ISO. *Environmental Management—Life Cycle Assessment—Requirement and Guidelines*; International Organization for Standardization: Geneva, Switzerland, 2006.
39. European Committee. *EN 15978:2011—Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method*; European Committee for Standardization: Brussels, Belgium, 2011; 60p.
40. ISO. Sustainability in buildings and civil engineering works. In *Core Rules for Environmental Product Declarations of Construction Products and Services*; International Organization for Standardization: Geneva, Switzerland, 2006.
41. Gu, H.; Liang, S.; Puettmann, M.; Pierobon, F.; Ganguly, I.; Chen, C.; Pasternack, R.; Wishnie, M.; Jones, S.; Maples, I. Mass timber building Life Cycle Assessment methodology for the US regional case studies. Sustainability special issue -Mass Timber and Sustainable Building Construction. *Sustainability* **2021**, in press.

42. Breneman, S.; Timmers, M.; Richardson, D. Tall Wood Buildings in the 2021 IBC Up to 18 Stories of Mass Timber 12. 2019. Available online: https://www.woodworks.org/wp-content/uploads/wood_solution_paper-TALL-WOOD.pdf (accessed on 11 August 2021).
43. Milota, M. Life Cycle Assessment for the Production of Pacific Northwest Softwood Lumber. 2020. Available online: https://corrim.org/wp-content/uploads/2020/06/CORRIM-AWC-PNW-Lumber.pdf (accessed on 10 August 2021).
44. Milota, M. Life Cycle Assessment for the Production of Southeastern Softwood Lumber. 2020. Available online: https://corrim.org/wp-content/uploads/2020/06/CORIRM-AWC-SE-Lumber.pdf (accessed on 10 August 2021).
45. Puettmann, M.E. Life Cycle Assessment for the Production of Northeast–Northcentral Softwood Lumber. 2020. Available online: https://corrim.org/wp-content/uploads/2020/06/CORRIM-AWC-NENC-Lumber.pdf (accessed on 10 August 2021).
46. Bare, J. TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0. *Clean Technol. Environ. Policy* **2011**, *13*, 687–696. [CrossRef]
47. SimaPro. *Simapro 9.1.1.1 Life-Cycle Assessment Software Package*; SimaPro: Amersfoort, The Netherlands, 2020.