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Wood buildings as a climate solution

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ABSTRACT

We conducted a systematic literature search and meta-analysis of studies with side-by-side life cycle analysis comparisons of mid-rise buildings using mass timber and conventional, concrete and steel, building materials. Based on 18 comparisons across four continents, we found that substituting conventional building materials for mass timber reduces construction phase emissions by 69%, an average reduction of 216 $kgCO_2e/m^2$ of floor area. Studies included in our analysis were unanimous in showing emissions reductions when building with mass timber compared to conventional materials. Scaling-up low-carbon construction, assuming mass timber is substituted for conventional building materials in half of expected new urban construction, could provide as much as 9% of global emissions reduction needed to meet 2030 targets for keeping global warming below 1.5 °C. Realizing the climate mitigation potential of mass timber building could be accelerated by policy and private investment. Policy actions such as changing building codes, including mass timber in carbon offset crediting programs and setting building-sector-specific emissions reduction goals will remove barriers to and incentivize the adoption of mass timber. Private capital, as debt or equity investment, is poised to play a crucial role in financing mass timber building.

1. Introduction

The buildings sector is a major source of global greenhouse gas emissions. Construction related CO_2 emissions equaled 5.7 billion tons, accounting for 23% of the emissions resulting from global economic activities in 2009 (Huang et al., 2018). More recently, in 2018, building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related CO_2 emissions (39%) (UNEP, 2019). The building sector takes on even greater significance when considering the approaching wave of 2.3 billion new urban residents (United Nations, 2019) who are expected to drive a doubling the global building stock by 2060 (World Green Building Council, 2019). Over the next decade, through 2030, the greatest increases in housing and infrastructure to accommodate growing urban populations are expected in China, North America and Europe (UNEP, 2017).

Despite its significance, most national plans for reducing greenhouse gas emissions (Nationally Determined Contributions) only mention buildings, falling short of setting sector-specific targets (UNEP, 2019). Lacking national plans, many cities, businesses, organizations, states and regions have developed their own building sector emissions targets. For example, with the aim of limiting global warming to under 2 °C, the World Green Business Council's Net Zero Carbon Buildings Commitment "challenges companies, cities, states and regions to reach net-zero operating emissions in their portfolios by 2030, and to advocate for all buildings to be net-zero carbon by 2050 (The Net Zero Carbon Buildings Commitment, n.d)."

Changes in all aspects of building operations—powering lighting, heating, cooling, etc.— will be required to achieve net-zero carbon buildings. This will mean increasing both energy efficiency and the generation and procurement of renewable energy (Wiik et al., 2018). As buildings become more energy efficient, embodied energy—that is, the energy used in the process of building material production, transportation, construction, maintenance, and demolition/re-use—assumes greater relative importance (Cabeza et al., 2014; Huang et al., 2018; Lolli et al., 2019). A building's embodied energy can be reduced by replacing carbon-intensive materials, like concrete and steel, with wood (Gustavsson et al., 2017; Sathre & O'Connor, 2010).

Until recently, wood was primarily used in the construction of single family or small multi-unit wood framed buildings (Brandner et al., 2016), limiting its potential in urban areas where new, low-carbon construction should prioritize larger mid-rise buildings (Churkina et al., 2020). However, the development of mass timber technology in recent decades

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has paved the way for constructing mid- and high-rise buildings with wood to meet the built environment demands of a rapidly growing global urban population (Brandner et al., 2016; Harte, 2017).

Mass timber is a category of wood-based framing characterized by the use of large solid wood panels for wall, floor and roof construction (Harte, 2017). In the construction of multifamily residential and commercial multistory buildings, cross-laminated timber (CLT) is the most widely used mass timber product (Brandner et al., 2016; Harte, 2017). Unlike concrete and steel, which emit CO_2 when produced, trees used to make mass timber products naturally absorb and store CO_2 as they grow. In sustainably managed forests, new trees are regenerated to replace trees that are harvested so that there is no net loss of forest carbon (Gustavsson et al., 2017). Increasing the amount of wood used in buildings, as a substitute for more carbon intensive materials, has the potential to decrease total emissions from the building sector (Hill, 2019).

At the global scale, estimates of the potential for wood buildings to serve as a climate solution range widely. Oliver et al. (2014) estimated that a 14%–31% reduction in global CO_2 emissions—or about 4.7–10.3 $GtCO_2$ $year^{-1}$ based on 2019 emissions (IEA, 2020)—could be realized by substituting wood for concrete and steel in building and bridge construction. The range reported by Oliver et al. was largely dependent on the efficiency of wood use inherent in different products (i.e., wood products where a larger proportion of harvested trees ends up in final product and bi-products are used to produce energy resulted in greater CO_2 emission reductions). The greatest reductions were achieved in flooring applications with engineered wood I-joists covered with plywood that was dried using wood energy, but CLT was not considered in the study (Oliver et al., 2014).

In a more recent study on the potential for wood buildings to serve as a climate solution, Churkina et al. (2020) found that construction of wood building for new urban dwellers could provide long-term carbon storage of 0.01–0.68 GtC/year in the buildings themselves. The variation in estimates demonstrates the inherent complexity of these studies and emphasizes the importance of consistent and systematic methods so that results can be compared (Chastas et al., 2018). The life-cycle assessment (life-cycle analysis or LCA) approach is widely viewed as best-suited for analyzing cradle-to-grave environmental impacts of buildings and has gained global support because the methods are relatively standardized (Lolli et al., 2019; Rønning and Brekke, 2014).

This study compares structure-level estimates of greenhouse gas emissions from building with wood to emissions from conventional materials like reinforced concrete. We systematically searched the literature to find side-by-side LCA comparisons with the two types of building materials and conducted statistical analysis of the pooled results to derive more generalizable conclusions about the climate mitigation potential of wood buildings (Binkley and Menyailo, 2005; Shelby and Vaske, 2008). Results from 18 comparisons were compiled and the differences in emissions between wood and conventional building materials during construction phase were analyzed using a linear mixed model. We estimated that, on average, building with wood can reduce greenhouse gas emissions by 216 $kgCO_2e/m^2$ of floor area, a 69% reduction compared to the estimated average construction phase emissions when conventional materials are used (95% confidence interval bounded by 146 and 287 $kgCO_2e/m^2$). By extension, we estimate that substituting mass timber for conventional building materials in half of expected new urban construction could account for 9% of the annual global emissions reductions needed between 2020 and 2030 in order to keep global temperature increases under 1.5 °C.

The remainder of the paper is organized as follows. In section two, we describe the methods for the systematic literature review, statistical analysis, and scaling-up low-carbon construction. In section three, we describe our results. Section four includes a discussion of the results and potential implications in the context of global climate as well as highlighting potential pathways, through policy instruments and private investment for realizing emissions reductions from wood-based construction. Finally, we conclude by summarizing the key points of the paper.

2. Methods

2.1. Systematic literature review

We conducted a systematic search of the literature for all the following combinations of terms: “mass timber” AND “life cycle analysis”; “mass timber” AND “life cycle assessment”; “mass timber” AND “LCA”; “cross laminated timber” AND “life cycle analysis”; “cross laminated timber” AND “life cycle assessment”; “cross laminated timber” AND “LCA”; “CLT” AND “life cycle analysis”; “CLT” AND “life cycle assessment”; “CLT” AND “LCA”. We used alternative forms, e.g. “CLT” and “cross laminated timber”, in an attempt to capture all relevant articles in the search. We used both “life cycle analysis” and “life cycle assessment” as these terms have been used to describe very similar analysis or used interchangeably. To ensure an adequate survey of literature we conducted the search using two different databases, Web of Science and Google Scholar. The search was carried out in October of 2019 and terms could appear anywhere in the text. Web of science yielded 55 returns and Google Scholar an additional 305 returns for a total of 360. We reviewed all items to isolate peer reviewed studies using LCA methods with side-by-side comparison of mass timber buildings to conventional building materials in structures with three or more stories. While differences in greenhouse gas emissions between mass timber and conventional materials has been documented during operations and end-of-life phases of buildings (Durlinger et al., 2013; Guo et al., 2017; Liu et al., 2016), we focused on studies for which construction phase data could be isolated. We limited the study to construction phase comparisons because: (1) it is most consistently reported in the literature; (2) it is the phase most affected by choice of building material; (3) it is the most relevant phase to achieve near and mid-term emissions goals; and (4) it is not subject to speculation about patterns in future consumption, building life-span, or material disposition (e.g., landfill, recycle, burn, burn for energy).

In the present study, we consider the construction phase to include emissions from building material production, all supply chain related transportation and actual erecting of the building. This definition of construction phase corresponds to modules A1-A5 as defined in the European standard EN 15804 (EN, 2012). However, the European standard is not utilized universally in the literature or in all parts of the world. The construction phase is also sometimes broken down into the “production” (of raw materials) and “construction” (building erection) phases (Tettey et al., 2019) and in other cases they are collectively referred to as the manufacturing phase (Ramesh et al., 2010). In other cases, the term “cradle-to-gate” is used to describe the complete production phase as described above without reference to the European standard modules (Sandanayake et al., 2018; Padilla-Rivera et al., 2018) while others exclude emissions from transportation to the building site and on-site building erection from “cradle-to-gate,” with (Skullestad et al., 2016) or without (Robertson et al., 2012; Zeitz et al., 2019) explicit reference to modules A1-A3. The inconsistent use of standards and terminology in the literature created some difficulty in setting common system boundaries to be included in our analysis. Ultimately, we included data from studies where we could isolate emissions on a $kgCO_2e/m^2$ of floor area basis with or without the inclusion of transportation to the building site and construction activities (Fig. 1). We included studies that did not consider transportation of building materials to the construction site or construction actives (A4&A5) because the relatively small proportion of onsite emissions associated with building erection as a share of total construction phase emissions. Further, there is evidence that the difference in transportation emissions between timber and non-timber building materials was expected to be minor. For example, Cole (1998) found that emissions during actual building construction ranged from 0.8 to 2.5 $kgCO_2eq/m^2$ for wood buildings using glulam structural frames overlaid with wood decking and 5 to 20 $kgCO_2eq/m^2$ for cast-in-place reinforced concrete walls. Dodoo (2019) estimated building construction to account for 5–6 $kgCO_2eq/m^2$ depending on the materials. Further, emissions from

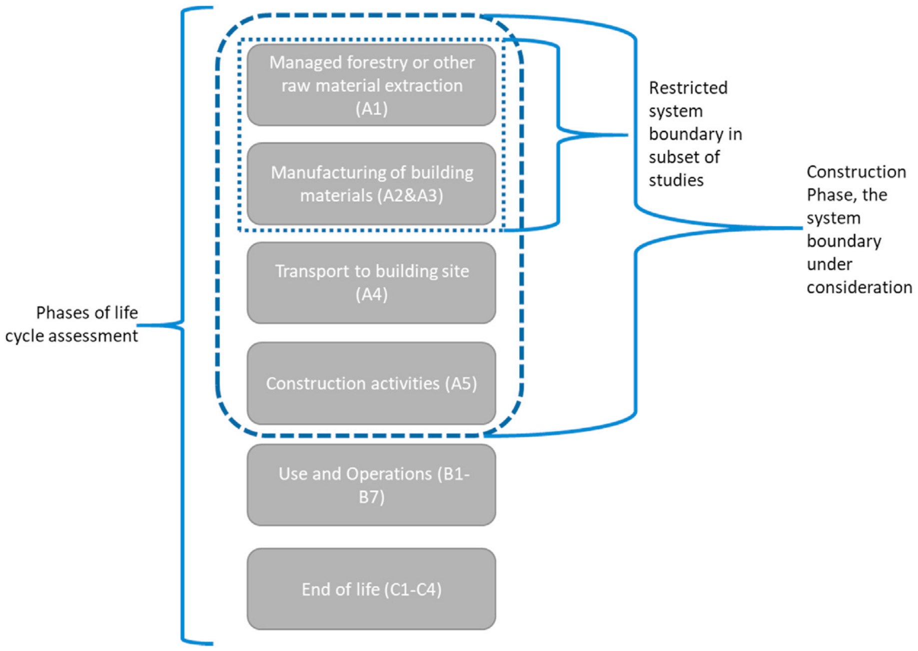

Fig. 1. Phases of a life cycle assessment and corresponding modules following EN 15978:2011 (2011). We analyzed studies reporting construction phase (within the system boundary) comparisons between wood and conventional materials in mid-rise buildings. A subset of the studies (Robertson et al., 2012; Skullestad et al., 2016; Zeitz et al., 2019) did not include emissions from transporting building materials to the construction site or emissions associated with on-site construction activities.

transporting materials to the construction site and erecting the building were often not reported separately from other construction phase emissions in studies that included them. The potential impact of this inconsistency was mitigated by our analytical approach of analyzing differences between within-in study comparisons of different materials rather than differences between the average emission for different building materials.

In total, 11 peer-reviewed publications detailing 18 comparisons met the criteria above. Construction phase emissions in units of $kgCO_2eq/m^2$ for the two types of building materials were compiled from the 18 comparisons along with supporting information like the total floor area, number of stories, type of building and region where the study was conducted (Table 1). Buildings used in the analysis ranged from 3 to 21 stories and from 1,140–29,100 m^2 of floor area. Building types included commercial, mixed-use, multi-unit residential and parking garages. The sample included one building from Australia, 6 from China, 7 from Europe, and 4 from North America (Table 1).

2.2. Statistical analysis

We specify a linear mixed model (LMM) to estimate the average difference in construction phase emissions between buildings constructed using wood and conventional building materials, β_1 below. The corresponding 95% confidence interval around the estimated coefficient β_1 provides a range of plausible values for the parameter. The LMM was estimated from 18 sample pairs of buildings drawn from the literature and specified as follows:

$$Y_t = \beta_{0+} + \beta_1 I.tim_t + (b_r)_t + c_t + \varepsilon_t$$

where

Y_t is the estimated CO_2/m^2 emissions of the *t*th building from the *r*th study; $r = 1, \ldots, 11$; $t = 1, \ldots, 36$
β_0 is the mean emissions of constructing buildings with conventional materials
β_1 is the incremental effect on emissions of constructing buildings with mass timber.
I.tim is a dummy variable equal to 1 for buildings constructed with timber and 0 otherwise
b_r is the random effect of the *r*th study
c_t is the random effect of the building size of the *t*th building
ε_t is the random error associated with the estimate of emissions of the *t*th building.

The residuals are assumed to be independent, normally distributed and with constant variance. Visual inspection of residual plots indicated that the assumptions of the LMM were adequately met except for normality. Despite the exception of the normality assumption, we opted to use the model because linear models are robust against assumptions of normality.

Typically, meta-analyses assign weights to results from different studies based on sample size and variance (Shelby and Vaske, 2008). Because each building comparison in our analysis is a single case study with no variance, there is no need to assign weights. While all studies employ a basic LCA framework, the assumptions underlying each study vary. Furthermore, even though each study is focused on the construction phase of building LCA there are still methodological differences in delineating system boundaries driven by researcher choices and variation in LCA protocol standards. The specific location of each study and the size of building considered could also impact emissions from transportation of raw materials and construction efficiencies. Assigning study and building size as random effects in an LMM allow us to account for some of the variability across studies. All statistical analyses were carried out using R Statistical Software (Team, 2017).

2.3. Scaling-up low-carbon construction

To illustrate the potential of mass timber as a climate solution, we put our results in the context of 2030 global emission targets to limit global warming to 1.5 °C. We begin by assuming 50% of new urban construction substituted mass timber for conventional building materials from 2020 to 2030. We select 50% of new urban construction as a benchmark not because we believe it is the most likely scenario but because we believe it is a feasible upper bound on the potential for mass timber as a substitute for conventional materials in the next ten years. Further, Churkina et al.

Table 1
Detailed list of studies included in analysis.

Paper	Region	Comparison(s)	Building size (m^2)	Number of floors
Dodoo (2019)	Europe	Reinforced concrete residential building with CLT redesign.	1140	4
Guo et al. (2017)	China	Four residential reinforced concrete buildings to CLT re-designs.	2636 4564 7134 10,990◊	4 7 11 17
Liu et al., 2016 [b]	China	Concrete residential building to CLT re-design in two different parts of China.	2799	7
Padilla-Rivera et al., 2018 [bd]	North America	CLT residential building to comparable concrete frame.	1512	4
Peñaloza et al., 2016 [b]	Europe	Simulated comparison of CLT residential building to concrete.	6078	12
Pierobon et al. (2019)	North America	Concrete office building to hybrid CLT re-design.	10,702	11
Robertson et al. (2012)	North America	Concrete-frame office building to CLT redesign.	14,233	5
Sandanayake et al. (2018)	Australia	Reinforced concrete commercial building to comparable CLT mixed use building.	Concrete was 17,104 CLT was 11,960	15 11
Skullestad et al. (2016) [c]	Europe	Four reinforced concrete buildings to CLT redesigns.	2613 6076 10,542 11,823	3 7 12 21
Tettey et al. (2019) [a]	Europe	Prefabricated concrete frame apartment building to CLT redesign.	1686	6
Zeitz et al. (2019)	North America	Post-tension concrete parking garage to comparable CLT parking garage.	Concrete was 29,100 CLT was 19,900	4 4

◊Details on building size from personal communication with the corresponding author.

┘Study included operational and end-of-life phases also.

[a] Study used both coal and fossil gas as a basis for substitution when calculating emissions, we used fossil gas number which were more conservative.

[b] Emissions numbers for construction phase were extrapolated from figures.

[c] Study included reference, best-case and worst-case scenarios, we used emissions from the "reference scenario" for analysis.

[d] Authors derived emissions for concrete comparison from another study.

(2020) suggest even higher levels of substitution may be feasible when considering slightly longer time-frame (30-years) and could be met sustainably from unexploited forest harvest potential. We estimate annual demand for new buildings over the next decade by multiplying the projected annual increase in global urban populations by the mean floor area per/capita of cities (30 m^2) (Churkina et al., 2020; United Nations, 2019). This assumes that the building space requirements for new urban dwellers will remain constant, which is reasonable given the relatively short projection period of 10 years. We then multiply 50% of annual demand by our estimate of annual emissions reductions for each year of the next decade to calculate total global annual emissions reductions from the substitution of mass timber in half of new urban construction. Finally, we compare annual emissions reductions from substituting conventional building materials with wood to the total annual emissions reductions needed to meet global 2030 emissions targets for limiting temperature rise to 1.5 °C, i.e. annual emissions decrease of 7.6% from 2020 to 2030 (see Supplementary Materials) (UNEP, 2019).

3. Results

The average difference in construction phase emissions between wood and conventional building materials was (−)216 $kgCO_2e/m^2$ of floor area ($p < 0.01$) and the 95% confidence interval was (−)146 to (−) 287 $kgCO_2e/m^2$ (Fig. 2). In other words, mass timber buildings emitted on average 216 kg CO_2e/m^2 less in construction phase than their counter parts constructed using conventional building materials. The estimate of the intercept, i.e. the average emissions using conventional materials after accounting for the random effects of study and building size, was 312 $kgCO_2e/m^2$ of floor area ($p < 0.01$). Thus, substituting conventional building materials with timber represents a 69% reduction in CO_2e emissions in the construction phase. The conditional R^2, an indicator of the proportion of variance in the response explained by the both fixed and random effects included in the model, was 0.78 (Lefcheck et al., 2016).

These results are consistent with Cadorel and Crawford's (2018) review of CLT LCAs which found substituting wood for conventional building materials results in reduces greenhouse gas emissions. In a review of global emissions from the construction sector, Huang et al. (2018) also conclude that substituting conventional building materials for those with low embodied carbon, like wood, is a key strategy to reducing global greenhouse gas emissions. Based on this estimate substituting wood for conventional building materials in 50% of new construction globally could meet 9% of annual emission reductions needed by 2030 to prevent temperatures from rising more than 1.5 °C. This result is similar in scale to estimates of potential stored carbon in buildings if 50% of new urban construction used substituted mass timber for conventional buildings materials (Churkina et al., 2020).

4. Discussion

All studies in our analysis found that mass timber buildings produce less emissions compared to reinforced concrete buildings in the construction phase. Some comparisons in our analysis included all building LCA phases—construction, operations (emissions during the operating

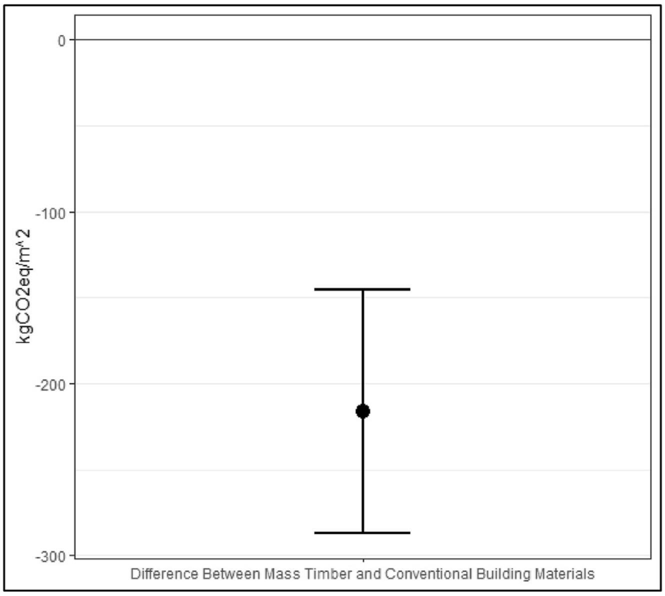

Fig. 2. Average difference in global warming potential during construction phase from building with mass timber compared to conventional materials (mass timber emissions – conventional building material emissions). The average difference equals a 216 $kgCO_2/m^2$ reduction, 69% of the estimated average construction phase emissions using conventional materials after accounting for random effects of study and building size which equaled 312 $kgCO_2/m^2$ (the zero-reference line above).

life the building, typically 50-years), and end-of life (emissions from demolition and material disposition)—and each concluded total lifecycle emissions were lower when building with mass timber compared to conventional materials. Further, all studies found that mass timber has the largest proportional benefit over conventional building materials in the construction phase (Tettey et al., 2019; Dodoo, 2019; Guo et al., 2017; Liu et al., 2016; Peñaloza et al., 2016).

Although the operational phase typically dominates total lifetime energetic and climactic impacts of buildings, these impacts are over many decades and as energy efficiency improves, construction becomes proportionally more significance (Cabeza et al., 2014; Thormark, 2002). In a meta-analysis, Ramesh et al. (2010) noted the construction phase accounts for 10–20% of the buildings' total lifecycle energy use. However, for a low-energy building Thormark (2002) showed that the share of the total lifecycle energy used in the construction phase may be as high as 45% of total lifecycle energy use. Further, the operation phase is typically based on a 50-year or longer building use cycle, a timescale which becomes less relevant in light of potentially catastrophic consequences from global warming if emissions are not curbed in the next 10 years (Global Warming of 1.5 °C —, n.d.). On the other hand, our scaled-up results suggest that substituting conventional building materials with mass timber could make substantial contribution toward achieving the near-term emission reductions necessary in order to prevent global warming from exceeding 1.5 °C.

Methods, including LCA boundary selection, varied somewhat between some studies highlighting the need in future research to further systematize protocol to facilitate easy comparisons. A great amount of variability can arise due to assumptions about carbon stored in wood building materials and whether it is treated as a credit or ignored based on the assumption that any stored carbon will be emitted at the end of life (Hill, 2019). To date, there is no consensus on methods for accounting of carbon stored in wood (Tellnes et al., 2017).

Reflecting this lack of consensus, the studies included in our analysis use a range of approaches to address stored carbon in wood building materials. Dodoo (2019), Padilla-Rivera et al. (2018), Pierobon et al. (2019), Sandanayake et al. (2018), (Ayikoe Tettey et al., 2019), and Zeitz et al. (2019) assumed no net biogenic carbon stored or released, i.e. bioproducts used in the construction phase were treated as carbon neutral and no credit was given for long term storage of carbon in building materials. In contrast, several studies assumed net carbon storage in wood building materials. Guo et al. (2017), Liu et al. (2016), and Robertson et al. (2012) all assume net carbon storage in wood building materials equal to 753–800 kg CO_2e/m^3. Extending this analysis, Peñaloza et al. (2016) and Skullestad et al. (2016) examined multiple scenarios where net carbon storage deviated from a carbon neutral baseline. For example, Peñaloza et al. (2016) included LCA scenarios where forests were considered in the LCA system boundary and they accounted for the timing of biogenic carbon sequestration by trees, duration of carbon storage in wood products and emissions. Skullestad et al. (2016) included approaches suggested by Guest et al. (2013) for incorporating biogenic carbon emissions and storage into LCA which resulted in the CLT building having negative emissions (i.e., they were a net sink) when biofuel from wood production substituted natural gas. In our analysis, if multiple scenarios were presented we used the data reported for scenarios where wood building materials were assumed to be carbon neutral, which were always the most conservative.

The treatment of carbon stored in long-lasting wood products like mass timber in LCA is not trivial. Churkina et al. (2020) estimated that potential for timber buildings to store as much as 0.68 Gt of carbon per year which would create a substantial carbon sink. However, carbon being stored in buildings is being transferred from forests, which also act as a carbon sink. Whether transferring carbon from the forest to the built environment will reduce atmospheric greenhouse gas concentrations depends on how the forest is managed and how long the building is in service (Guest et al., 2013; Gustavsson et al., 2017). For example, if the wood used to make mass timber is taken from a forest that is replaced with agriculture after harvest (deforestation) then the land-use change related emissions and emissions from manufacturing the timber products will likely more than offset the long-term storage benefits. The use of mass timber that is certified sustainable by a reputable certifying body with a chain of custody standard, such as Forest Stewardship Council or Sustainable Forestry Initiative, virtually eliminates that possibility.

The relative lifespan of a mass timber building and the length of the forest rotation (number of years between planting and harvesting) will also influence the potential climate benefits from building with wood. If the lifespan of the building is shorter than the average rotation in the forest and the carbon in the wood is re-emitted to the atmosphere when the building is demolished, then total carbon storage would be less than if the forest was not harvested and simply left to grow (Guest et al., 2013; Skullestad et al., 2016). However, if the lifespan of the building is longer than the average rotation in the forest providing the wood, then total carbon storage between the two sources should be treated as a sink (Guest et al., 2013; Skullestad et al., 2016). This implies that increasing the lifespan of mass-timber buildings and simultaneously accelerating the growth of the forests generating the raw material will increase the importance of wood building's carbon storage potential.

When considering long-term carbon storage potential, it is also important to account for the size of the respective carbon pools, in both the forest and built environment. Law et al. (2018) point out that some forest systems have the capacity to store much more carbon than they do under sustainable short-rotation production forestry but Churkina et al. (2020) challenge that the carbon storage density of mass timber buildings is comparable or even larger than some of the most carbon dense forest systems in the world. Another important consideration is the growth rate of the forest pool. Moving carbon from the forest pool to the built environment pool is more likely to have a global warming benefit if the harvested trees are growing slowly and harvesting and regenerating the forest will lead to more rapid carbon accumulation in the forest (Gustavsson et al., 2017). These complicated interactions between the carbon pools in timber buildings and the forest suggest incorporating forests into LCA system boundaries and utilizing dynamic methods that track sequestration and emissions over time could provide important information for decision makers (Peñaloza et al., 2016).

Some authors have suggested that LCA analysis be viewed cautiously. Harmon (2019) conducted a sensitivity analysis around LCA assumptions for mass timber construction and concluded that GHG benefits compared to concrete and steel may be overestimated 2–100 fold. Harmon's (2019) conclusions are based on challenging the assumptions implicit in many LCA substitution studies that carbon displacement value remains constant, the displacement is permanent without leakage and that there is no relationship between building longevity and substitution longevity. However, even if these assumptions do not hold, the over-estimates Harmon projects take 300-years to accumulate and have negligible impact on estimates of construction phase substitution benefits in the first ten years, which is the critical period considered here. Zeitz et al. (2019) also downplay the benefits of mass timber, demonstrating that the composition of concrete and steel had a large impact on analysis and when best practices for both conventional and mass timber materials are used, differences in global warming potential between the two become very small. Zeitz et al.'s results are important but only represent a single case which has been included in our metanalysis. The impacts of building with mass timber can fluctuate regionally and depend on many factors like the availability of materials, transportation, manufacturing and regional energy sources. Thus, when considering potential global impacts, meta-analysis like this study represent pooled knowledge and the highest level of expert confidence (Binkley and Menyailo, 2005).

Co-benefits and trade-offs of building with mass timber should be considered in conjunction with climate impacts. Mass-timber outperformed re-enforced concrete with respect to other LCA environmental indicators including reduced smog potential, reduced ecological toxicity, reduced acidification potential, reduced ozone depletion potential, and improved human health effect potential (Durlinger et al., 2013; Pierobon et al., 2019; Robertson et al., 2012). Mass-timber has comparable constructions costs to conventional building materials but can reduce construction time for mid- and high-rise buildings, which may make it an attractive alternative from an investment perspective (Cazemier, 2017; Mallo and Espinoza, 2016). The aesthetic and acoustic properties of buildings with interior exposed wood surfaces are also desirable (Espinoza et al., 2016; Laguarda Mallo and Espinoza, 2015; Mallo and Espinoza, 2016). Building with wood has desirable seismic properties (Brandner et al., 2016) but concerns still remain regarding perceived durability and fire risks relative to conventional building materials (Kremer and Symmons, 2018). There are also likely trade-offs in other ecosystem services when forests are managed to maximize carbon benefits from wood utilization (Himes et al., 2020).

Finally, we recognize the important role of both policy and private investment in order to scale-up low-carbon construction. First, removing policy barriers to the deployment of mass timber, such as building standards codes and site permitting, would increase industry adoption and familiarity among architects, developers and construction companies in turn (Espinoza et al., 2016; Kremer and Symmons, 2018; Laguarda Mallo and Espinoza, 2015). Second, the introduction of both regulatory and market-based policies could be used to further unlock the climate mitigation potential of mass timber building. Within a regulatory framework, building-sector-specific targets that include long-term carbon storage in wood could be incorporated into national carbon plans (NDCs). In addition, incorporating mass timber into existing offset crediting programs (voluntary or compliance) would immediately incentivize the use of wood building materials.

Alongside policy changes, private capital, as equity or debt investment, may also play a critical role in unlocking the climate mitigation potential of substituting wood for conventional building materials. For example, the development of institutional scale investment opportunities in sustainable, low-carbon buildings could help investors achieve both financial and climate targets along with the portfolio benefits of real estate. On the debt side, green bonds could provide an effective way to finance large-scale wood buildings, similar to green bonds for energy efficiency upgrades in buildings, which totaled $47 billion (USD) in 2017 (IAE and UNEP, 2018). Further, for investors with climate or portfolio decarbonization targets, both equity and debt investment in mass timber building could provide assurances that their investment will contribute to measurable emissions reductions.

5. Concluding remarks

- According to our meta-analysis, substituting conventional building materials with mass timber in mid-sized urban construction reduces construction phase emissions by an average 216 $kgCO_2e/m^2$ of floor area, a 69% reduction. Studies included in our analysis were unanimous in showing emissions reductions when building with mass timber compared to conventional materials. The importance of this reduction increases as buildings become more energy efficient and the need to reduce emissions becomes more eminent.
- Although the LCA methodologies are relatively standardized, variation in approaches taken by researcher still exist which have substantial impact on individual study results. The variation between individual studies can also arise from context specific parameters, like resource availability and transportation distance. By incorporating the results from multiple individual studies in a single analysis we provide a more generalizable estimate of potential global benefits of substituting conventional building materials with mass timber.
- We estimate that substituting conventional building materials with wood in half of new urban construction could provide 9% of global emissions reduction needed to meet 2030 targets for keeping global warming below 1.5 °C. This could be a substantial piece of the emission reduction portfolio needed to meet the ambitious 2030 target without substantial changes to consumption, life-style or policy. Almost a tenth of necessary emissions reductions could come from choosing a different material for expected urban construction that will occur one way or the other.
- Realizing the climate mitigation potential of mass timber building may be supported by both policy and private investment. Allowing for the incorporation of mass timber in building codes, carbon offset crediting programs and building sector emissions reduction goals will remove barriers and incentivize greater adoption of mass timber. Private capital in the form of institutional scale investment or green bonds could play a crucial role in financing mass timber building.

Author contributions

Austin Himes roles: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing- original draft; Writing- review & editing.

Gwen Busby roles: Conceptualization; Investigation; Project administration; Supervision; Writing- original draft; Writing- review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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