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Low-carbon concrete has the potential to meet global urban housing needs by 2050



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Meeting the growing demand for urban housing is a global sustainability challenge. Numerous studies have concluded that bio-based materials are lower carbon options compared to concrete while disregarding resource availability and harvesting emissions. This study evaluates low-carbon concrete in comparison to engineered bio-based materials and stabilized earth blocks for three issues: embodied carbon, material supply limitations and production scalability. Bio-based materials could only supply <14% of global demand due to limited forest area within assumed conditions of sustainable harvesting yields. In contrast, adoption of low-carbon concrete is not resource-limited, with potential savings of 14.3 Gt.CO₂(eq.) achievable versus benchmark concrete housing from 2025–2050. Furthermore, engineered biomaterial production would need to scale up faster than low-carbon concrete, while also overcoming greater logistical and social barriers. To meet urban housing needs, low-carbon concrete is not perfect but is the lowest-carbon option that can be scaled-up to meet global demand by 2050.

There is an urgent need to decarbonize the built environment^{1,2}, whilst also meeting societal needs and staying within other planetary boundaries. The majority of future housing demand is projected to be in urban areas and largely within economically developing countries in Asia and Africa³. Concrete is the most widely used material by volume in construction worldwide, accounting for ~50 wt.% of all anthropogenic material stocks⁴. Numerous decarbonization strategies exist for concrete, many of which are already technically and economically feasible^{5,6}. Bio-based materials (e.g., cross-laminated timber, laminated veneer bamboo) and earth-based materials (e.g., cement-stabilized soil blocks) are often advocated as alternatives for concrete in housing. Assessments of the relative technical performance and embodied carbon of different materials are typically carried out for an individual structure^{7–9}. These studies have typically concluded that bio-based materials are beneficial for embodied carbon within the scope of Cradle-to-Site (i.e., life cycle stages A1–A5 in EN 15978), relative to a benchmark concrete-based structure. Building-level findings have led to recommendations to rapidly expand the use of bio-based construction as a climate mitigation solution in the coming years^{10,11}.

The literature in this area typically has three limitations. First, studies have generally compared bio-based construction to conventional concrete construction. Typically, a mean value for embodied carbon of concrete is calculated, bounded by minimum and maximum values that are deemed representative of variation in industrial concrete, e.g., refs. 12,13. However, these scenarios do not consider low-carbon innovations that are technically

and economically viable now and are more representative of concrete construction in the years to 2050^{6,14}. Introducing a low-carbon concrete material typology into global housing models, alongside a “business as usual” concrete benchmark, would better reflect the reality of current developments in construction materials.

Second, for bio-based materials, many studies ignore the impact of harvesting wood and the resulting release of biogenic carbon into the atmosphere^{15,16}. The majority of studies do not attempt to estimate the changes in biogenic forest stocks relative to the alternative scenario in which no harvesting took place¹⁷—this leads to underestimation of the real impacts, and hence to frequent overestimation of the net climate benefits of wood-based construction products¹⁸. In general, when reductions in the total storage of carbon are properly accounted for, multiple studies have concluded that use of biomaterials for construction *increases* carbon in the atmosphere for decades^{19–21}. The inclusion of harvesting costs is important to assess the true embodied carbon of bio-based construction (Larasatie et al.²²; Robati and Oldfield, et al.²³).

Third, for the most part, existing literature fails to address the limitations of bio-based materials supply on a global scale and the practicalities of quickly upscaling bio-based construction. One exception is Pomponi et al.²⁴, which concluded it would be unrealistic to assume that more than a minor proportion of construction could be covered without unacceptable impacts to forest ecosystems, given recent track records of forestry management. Churkina et al.²⁵ and Mishra et al.¹⁰ proposed it would be feasible to supply

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up to 90% of new urban housing in wooden buildings, but doing so would require conversion of vast areas of natural tropical forests to plantations, with drastic implications for biodiversity. The feasibility of scaling up production to meet demand in the near future is a particularly neglected issue. The mechanisms of transition of socio-technical systems to a low-carbon future, and associated barriers, are increasingly recognized as important in terms of assessing the viability of a given transition and how support can be best given²⁶. Such critical assessments have been extensively carried out for other sectors, including transport²⁷ and energy²⁸, but are lacking for low-carbon construction materials.

This study first investigates the embodied carbon of a single housing unit for five different material typologies, including the influence of carbon accounting methodology:

1. business as usual concrete (concrete-BAU)
2. low-carbon concrete (concrete-ECO)
3. cross-laminated timber (timber-CLT)
4. laminated veneer bamboo (bamboo-LVB)
5. stabilized earth block (earth-SEB)

A 4-storey apartment archetype (Fig. 1) was used as a reference housing unit for this analysis, as mid-rise housing is proposed to be the most sustainable generic form of urban housing in terms of operational energy²⁹ and urban form³⁰. In addition, high-rise housing is not yet widely achievable for bio-based materials²⁵, so mid-rise housing is a suitable archetype to compare the range of different material typologies considered in this study. The archetype was designed to meet the structural requirements of the Eurocode, and the material intensity values (i.e., mass of material per unit area of floor space) were within the range found in the literature (Supplementary Fig. S1 and Supplementary Table S1). In the second part of the analysis, we assess the likely limitations on material supply in relation to projected urban housing demand to 2050, based on existing models for urban housing demand and forest area. Lastly, we evaluate the opportunities and drawbacks for rapid scale-up of the relevant material sectors, based on their current logistical structures and production capacities.

Results

Three inorganic material typologies were evaluated: Earth-SEB, Concrete-BAU, and Concrete-ECO. The rationale for assumptions of specific material properties and their numerical values are provided in the “Methods” section and Supplementary Table S3, respectively. These three material typologies did not include any bio-based materials within the structural components considered, so only production emissions were calculated. A sensitivity

analysis for production emissions was undertaken using the same approach described for the bio-based material typologies above.

Stabilized earth blocks (Earth-SEB) have been proposed as “low-carbon materials”; here, 7 wt.% low-carbon cement was used to stabilize compressed earth blocks, which are then used for the load-bearing walls of the structure (Fig. 1). 7 wt.% cement is the minimum value required to achieve the target compressive strength of SEBs for the structural design.

The business-as-usual concrete material typology (Concrete-BAU) consists of conventional reinforced concrete foundations, slabs, and columns, and wall infill of fired clay bricks with Ordinary Portland Cement mortar. This typology is typical for urban mid-rise construction in urban areas worldwide.

The low-carbon concrete material typology (Concrete-ECO) adopts three principal strategies which are technically feasible and economically viable: lower average global binder content (304 kgm⁻³ vs. 351 kgm⁻³), achievable by improved concrete mix design and use of admixtures⁶; lower clinker content (50 wt.% vs. 75 wt.%), achievable by replacement of clinker e.g., with calcined clay and limestone (LC³)¹⁴; and, the replacement of fired clay bricks with low-carbon concrete blocks for infill walling. The concrete used in the Concrete-ECO typology is considered to be more representative of concrete used towards 2050 compared to conventional concrete in the Concrete-BAU typology; the replacement of fired clay bricks with concrete blocks is anticipated to achieve notable savings in embodied carbon³¹.

The Concrete-ECO housing has less than half the embodied carbon of Concrete-BAU. The Earth-SEB typology production emissions (252.6 kg CO_{2(eq)}m⁻²) are higher than for Concrete-BAU (220.6 kg CO_{2(eq)}m⁻²). Stabilized earth blocks are often promoted as low-carbon alternatives to fired bricks³²; fired bricks are commonly used in housing construction as masonry walling materials across the globe, and can have extremely high production emissions when inefficient kiln technologies are used³¹. Whilst stabilized earth blocks can be lower-carbon alternatives to fired bricks³³, this comparison shows that they are not necessarily a lower-carbon alternative to conventional concrete construction. This partly arises because the use of cement for earth stabilization is less efficient in imparting strength compared to the use of cement in concrete^{34,35}.

To investigate the effect of using different biogenic carbon accounting approaches on the embodied carbon of the five material typologies for a unit of urban housing over a 50-year service life, the following three methodologies were applied to the two bio-based material typologies, Timber-CLT and Bamboo-LVB (detailed descriptions provided in the “Methods” section, and schematic illustration in Supplementary Fig. S2).

Fig. 1 | A visualization of the 4-storey housing archetype used in this study, and a description of the materials used in each of the main structural elements within each of the five material typologies. PC portland cement, CLT cross-laminated timber, LVB laminated veneer bamboo.

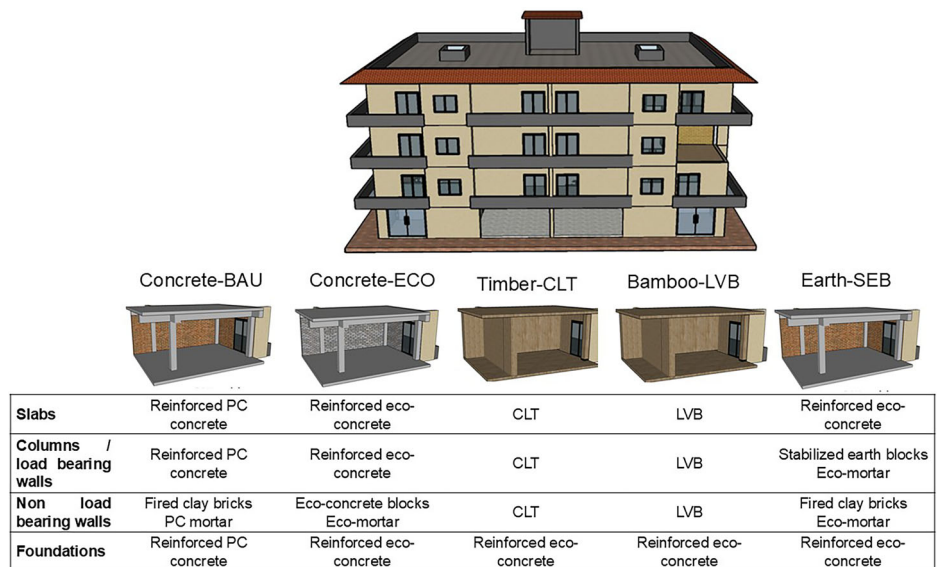
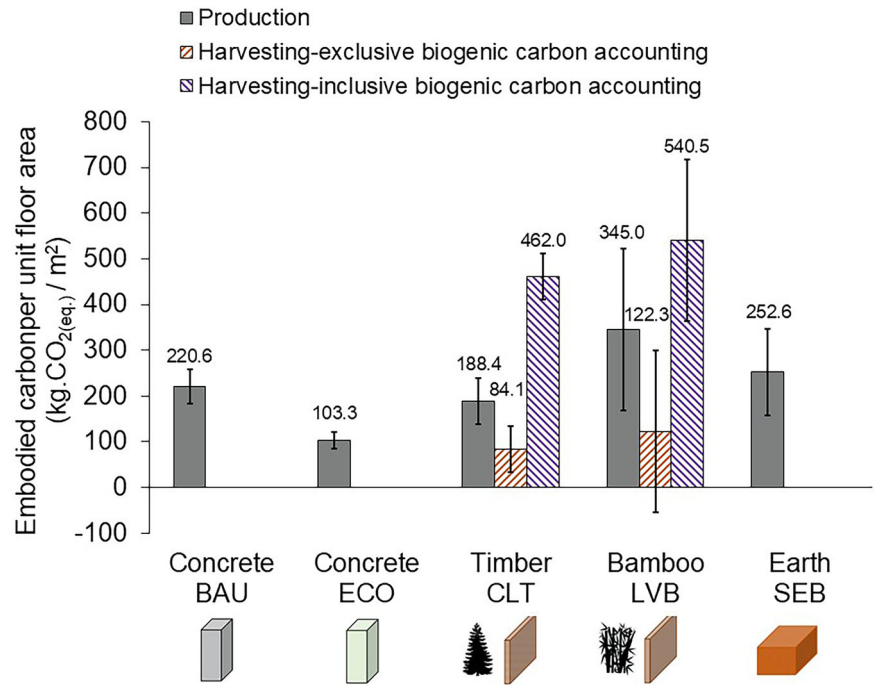


Fig. 2 | The values of embodied carbon per unit floor area for the five material typologies. The results show the three different carbon accounting approaches considered in the study.



Production emissions only

CO_{2(eq.)} emissions associated with the material inputs and manufacturing processes required to produce the construction materials for one unit of housing in each typology (excluding biogenic carbon flows), i.e., A1–A3 life cycle stages. The production emissions from engineered bio-based materials arise from the transportation hauls, the energy required for the forestry operations, manufacturing, and forming processes, as well as the glues and resins used to bind the laminate layers together, and the steel connections required between elements; differences in production processes lead to variation in production emissions between different sites and products^{36,37}. Bio-based materials’ emissions are typically reported after summation with estimated sequestration^{13,37}, so the comparison solely of production emissions is rarely undertaken.

Harvesting-exclusive biogenic carbon accounting

CO₂ sequestration associated with re-growth in harvested forests is allocated to bio-based material products, calculated using a semi-static approach³⁸, that considers the lifetime of the building and the rotation period of forest harvesting. It is assumed that at the end-of-life, the biogenic carbon sequestered within the bio-based materials themselves is released into the atmosphere; the resulting sequestration is a result of the service life being longer than the rotation period (see “Methods” section for details). Production emissions are included, but harvesting costs are excluded. Under this approach, in theory, 100 tons of carbon could be removed from a forest, 99 tons released to the atmosphere (from decomposing roots and slash, bark and other wood burned as by-products), and one ton stored in a building; but instead of counting this change as a net loss of 99 tons of carbon, it is counted as a net gain of one ton of carbon. We deem this approach to be an unrealistic simplification compared to physical reality, but we include it in this comparison as it remains a widely used approach.

Harvesting-inclusive biogenic carbon accounting

CO_{2(eq.)} emissions arising from the loss of carbon stocks from forest soil and residues (e.g., roots, foliage) during harvesting are allocated to bio-based material products, calculated using the CHARM model³⁹. Sequestration associated with the re-growth of harvested forests (as described above) is also allocated to bio-material products, and production emissions are also included. The CHARM system-level model accounts for the changes in

different carbon pools, building on an approach that was developed in the 1990s⁴⁰ and has also been adopted in previous models for timber products (e.g., refs. 41,42).

The embodied carbon values for the Timber-CLT and Bamboo-LVB material typologies change dramatically depending on the accounting methodology used (Fig. 2). A harvesting-inclusive approach gives values that are over four times higher than the harvesting-exclusive approach. To test the robustness of these findings to variation in embodied carbon of the constituent materials, a sensitivity analysis on the inventory data was carried out. Upper/lower scenario values for each constituent material, corresponding to one standard deviation above/below the mean, as calculated from the range of literature values (for full description see “Methods” section). The range of values for the upper/lower scenarios are shown as error bars in Fig. 2. The range between the upper and lower scenarios was highest (± 354.9 kg CO_{2(eq.)}m⁻²) for bamboo-LVB. A previous systematic review of 33 papers on engineered bio-based materials showed a variation of 50% to –125% in the inventory data compared to the average carbon intensity⁴³. A major contribution to this variation arises from differences in process efficiency, and valorization routes for residues generated in factory processing—particularly whether they are incinerated as fuel, or used in other bio-based products such as particle boards³⁶. The variability in production emissions explains how, when summed with sequestration values only as the harvesting-exclusive approach, false conclusions could be drawn on the possibility of bio-based materials buildings being carbon-negative (Fig. 2).

Using harvesting-exclusive biogenic carbon accounting, the Timber-CLT (84.1 kg CO_{2(eq.)}m⁻²) and Bamboo-LVB typologies (122.3 kg CO_{2(eq.)}m⁻²) appear to offer carbon savings over the Concrete-BAU typology (220.6 kg CO_{2(eq.)}m⁻²) (Fig. 2). The apparent savings seen here are of the same magnitude as other studies that use harvesting-exclusive biogenic carbon accounting to compare bio-based construction to conventional concrete construction^{44–46}. However, as previously explained, these apparent savings are not deemed realistic, as they exclude the carbon cost of harvesting.

Using harvesting-inclusive biogenic carbon accounting, the emissions per unit floor area of the Timber-CLT (357.7 kg CO_{2(eq.)}m⁻²) and Bamboo-LVB typologies (317.8 kg CO_{2(eq.)}m⁻²) are considerably higher than those of the Concrete-BAU typology (220.6 kg CO_{2(eq.)}m⁻²) (Fig. 2). This conclusion, that construction using engineered bio-based materials has higher

Table 1 | Displacement factors (also referred to as substitution factors) for the Timber-CLT and Bamboo-LVB material typologies

Reference typology	Bio-based typology	Production emissions only	Harvesting-exclusive biogenic carbon accounting	Harvesting-inclusive biogenic carbon accounting
Concrete-BAU	Timber-CLT	0.07	0.28	-0.49
	Bamboo-LVB	-0.18	0.14	-0.46
Concrete-ECO	Timber-CLT	-0.17	0.04	-0.73
	Bamboo-LVB	-0.35	-0.03	-0.64

Values are given for the three carbon accounting approaches. The Concrete-BAU and Concrete-ECO typologies are used as non-bio-based reference typologies. Details of calculations are stated in the Methods section.

embodied emissions than conventional concrete-based construction, is in agreement with the few previous studies which do adopt a harvesting-inclusive approach^{13,21,37}.

When comparing the Concrete-ECO typology with the bio-based typologies (Timber-CLT and Bamboo-LVB), the choice of biogenic carbon accounting approach is critical. If using a harvesting-exclusive biogenic carbon accounting, there is an apparent modest saving for Timber-CLT (84.1 kg CO_{2(eq)}m⁻²) compared to Concrete-ECO (103.3 kg CO_{2(eq)}m⁻²). If using harvesting-inclusive biogenic carbon accounting, the embodied carbon of the Timber-CLT (462.0 kg CO_{2(eq)}m⁻²) and Bamboo-LVB (540.5 kg CO_{2(eq)}m⁻²) typologies are both substantially higher than Concrete-ECO (and also Concrete-BAU).

Displacement factors, also referred to as substitution factors, are widely used to compare the effects of substituting bio-based construction products on a structure’s embodied carbon, in comparison to a reference structure that includes non-bio-based products^{18,47}. A wide range of substitution factors are found in the literature for structural products (-0.9 to +5.5 reported by Leskinen et al.⁴⁸), partly arising due to inconsistencies in boundary conditions, assumptions, and units, as well as real differences in primary data^{18,48,49}. When Concrete-BAU is used as a reference typology (Table 1), harvesting-exclusive carbon accounting gives positive values (0.28 for Timber-CLT, 0.14 for Bamboo-LVB), whereas harvesting-inclusive carbon accounting gives negative values (-0.49, -0.46). This means that per unit mass of CLT (in t.C) used in the Timber-CLT low-rise housing structure, the embodied carbon of the structure is increased by 0.49 t.C compared to the Concrete-BAU structure. Higher negative displacement factors (-0.73, -0.64) indicate that replacing Concrete-ECO structures with bio-based typologies substantially increases the embodied impact. In summary, the choice of biogenic carbon accounting methodology is a critical factor in determining the embodied carbon of engineered bio-based materials; yet even when a harvesting-exclusive accounting methodology is used, the Concrete-ECO typology had similar emissions to Timber-CLT and Bamboo-LVB typologies.

The resource capacity of engineered bio-based materials to meet future urban housing demand was estimated by calculating their maximum annual production within constraints of existing forest areas, responsible harvesting practices, and manufacturing efficiency (details in “Methods” section). An important assumption in this study was that no large-scale afforestation will take place up to 2050, and so existing projections for forest area were adopted⁵⁰; this is a key difference compared to other studies whose outcomes have been more positive for bio-based materials^{10,25}. We did not consider that a large-scale afforestation scenario was realistic to consider in this study, for several reasons. The challenges and complexity of mass afforestation are considerable⁵¹, with known knock-on consequences, e.g., an increase in food prices⁵². Even if mass afforestation were carried out, the advantages in sequestration from leaving new forests to grow to maturity would likely outweigh any substitution benefits from using them in construction⁵³. Anthropogenic activities have already pushed land-system change beyond the planetary boundaries of known safe operating space⁵⁴, with forest cover an aspect of particular importance. Yet there is still net global deforestation (-4.7 million ha/year over 2010–2020⁵⁵) with ongoing competition from

multiple sectors and actors for forest area, such as agriculture⁵⁶. Furthermore, even if mass afforestation were carried out immediately, there would not be enough time for the forests to grow sufficiently to allow for use in structural construction products by 2050 (i.e., a growth period of 25 years), the assessment year used in this study.

Over the period of 2025–2050, it is estimated that 7.18 billion m³ of CLT and 0.44 billion m³ of LVB could be supplied from existing forest resources worldwide (Fig. 3); together, this could fulfill 13.7% of worldwide demand for additional urban floor area over this period, under the median population (i.e., SSP2) scenario. This low resource potential can partly be explained by the large amount of forest area required to provide a single unit of the housing archetype considered here (184 ha for Bamboo-LVB, 1,138 ha for Timber-CLT), under sustainable harvesting practices (Fig. 4). This scenario of maximum production would still leave 86.3% of demand unfulfilled, corresponding to a shortfall of 48.1 billion m³ of bio-based materials. And it is important to note that this maximum rate of timber harvesting would be >10 times greater than the current global, annual timber production of ~3.6 billion m³/year for industrial roundwood and fuel combined³⁹. From a global perspective, bio-based materials could make a minor contribution, at most, to urban housing demand. Previous studies have concluded similarly: Pomponi et al.²⁴ suggested only 11% of the global demand for housing could be met with CLT, and Zhong et al.² assumed that 10% was a reasonable value for global CLT substitution for concrete across buildings and infrastructure. LVB has received much less research attention than CLT. The only known study on global scalability of bamboo-based construction claims that existing bamboo resources are sufficient to meet half of global demand for housing by 2050⁵⁷; we deem this value to be unrealistically high in comparison to the 0.8% upper limit calculated in the present study.

Comparing world regions, bio-based materials could potentially fulfill the highest proportion of demand in Latin America (36.5%) and Europe (25.8%) (Fig. 3). However, the predicted demand for additional urban housing as a fraction of global demand is relatively low for Latin America (9.2%) and Europe (14.0%). In contrast, the proportion of material demand that could potentially be met by bio-based materials is among the lowest for the Middle East & Africa (13.3%) and Remaining Asia (excluding China) (9.0%); these two regions are among regions with the highest predicted demand for additional urban housing as a fraction of global demand (16.7% for Middle East & Africa, and 25.5% for Remaining Asia). Due to the absence of region-specific data for the material intensities, the demand-supply ratio is a function of the available forests and demand for housing. Hence, the findings agree well with previous regional supply:demand analyses^{2,24}. Whilst some regions within China and Asia have plentiful bamboo resources, the global potential contribution of bamboo is highly limited due to the relatively small area of bamboo forests worldwide in relation to timber forests. The supply of engineered bamboo is subject to the assumed harvest yield, industrial process efficiency, and market split against other products. Limitations also exist around the species of bamboo that are known to be suitable for use in engineered structural products⁵⁸. These data indicate that the geographical distribution of forest resources (at the scale of global regions) is not well aligned with the anticipated demand for

Fig. 3 | Regional supply-demand plots for CLT and LVB, showing the potential quantities (Bm³) of bio-based materials that could be supplied from 2025 to 2050 and the remaining unmet demand, in absolute and proportional values. Numerical values on pie charts are in units of Bm³.

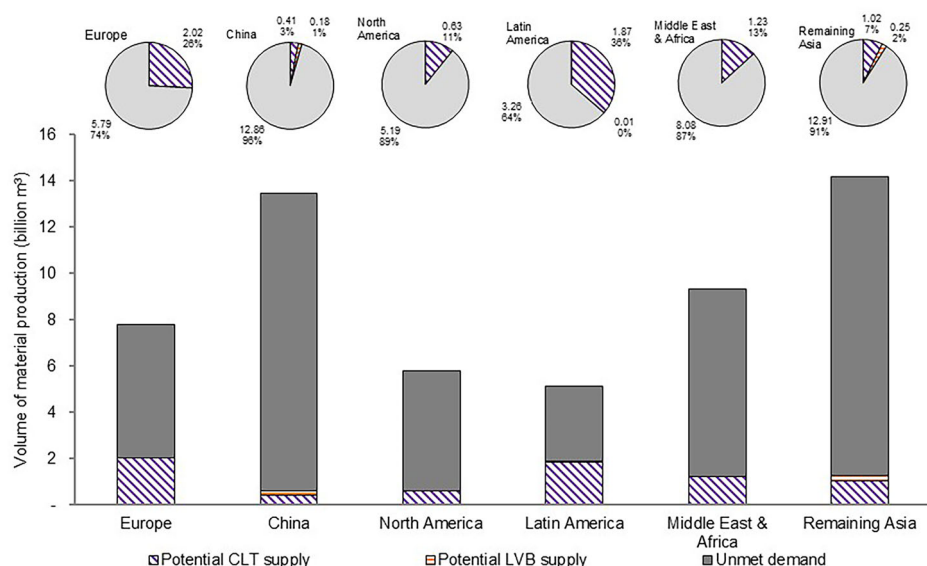
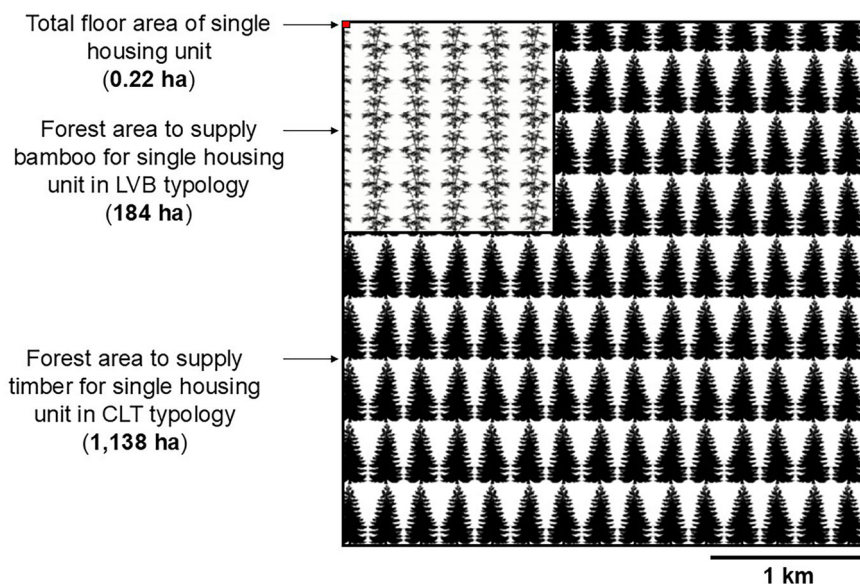


Fig. 4 | The forest areas (100 ha = 1 km²) required to supply sufficient volumes of biomass to construct a single unit of the 4-storey housing archetype using bamboo-LVB and timber-CLT, for an annual harvest of forests that are managed in a sustainable way. See “Methods” Statement for full calculations.



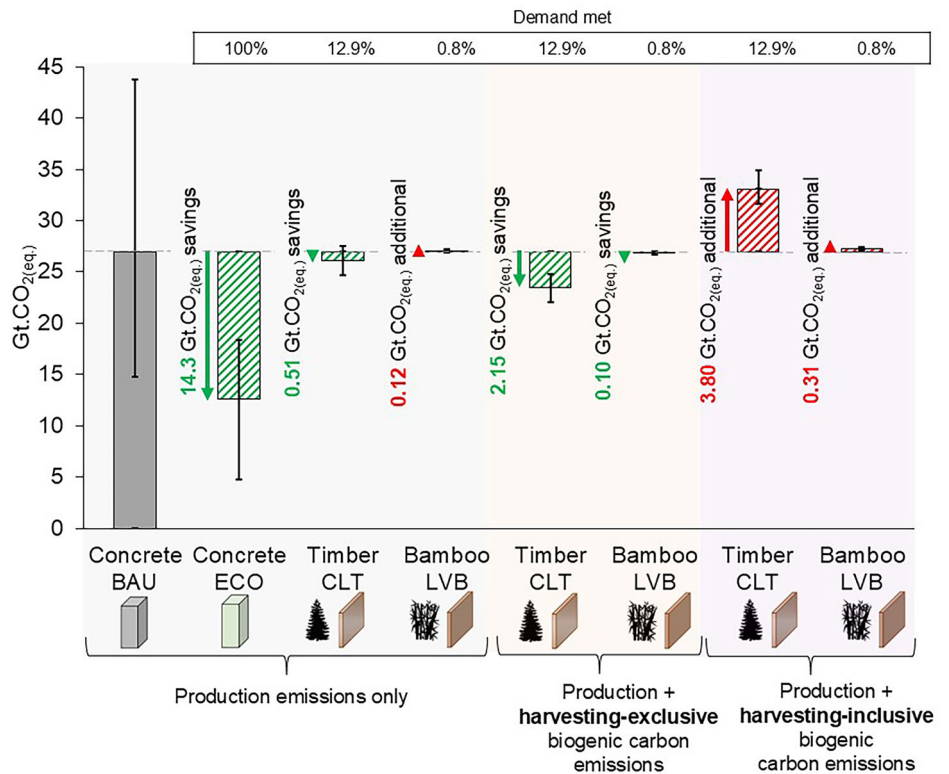
additional urban housing. As a general trend, the potential for bio-based materials supply is lowest in the regions where the demand for additional urban housing is greatest, as previously observed²⁴. Carbon emissions associated with intercontinental transport of CLT can exceed their Cradle-to-Gate carbon emissions⁵⁹. Hence, for environmental and affordability reasons, transportation of large volumes of bio-based materials between world regions is undesirable.

The current global supply of conventional cements is estimated as ~4.2 Gt/year⁶⁰. Expansion of production is expected in Africa, India, and other areas of Asia, with overall production projected to increase to 4.7–5.2 Gt/year by 2050⁶⁰. The primary raw materials of clay, shale, limestone, and gypsum are abundant at the global scale; however, some regions face issues with the location and quality of deposits, and other regions may face challenges to maintaining or increasing production levels for particular constituents, including water⁶¹ and sand⁶². Nonetheless, the clays and limestone suitable for LC³ cement are estimated to be available in more than sufficient quantities in the areas where most population growth is predicted¹⁴. On a global scale, the geographical distribution of geological resources aligns

more closely with the distribution of urban growth compared to forest resources.

The implications of structural material selection for the embodied carbon emissions of urban housing on a global scale were then investigated. The embodied carbon values for a single housing unit (Fig. 2) were applied to the gross floor area increase for urban housing projected globally to 2050; the maximum feasible supply of each material typology was determined within the resource limits relevant for each material typology (Fig. 3). Given inherent uncertainties around the typology distribution of future housing, population growth, changes in forest area and carbon factors, this approach is intended to be indicative, rather than a precise forecast per se. The potential impacts on carbon emissions for each material typology were estimated relative to a concrete-BAU reference scenario, including the effect of different carbon accounting methodologies (Fig. 5). The range of uncertainty for each alternative scenario was estimated based on the cumulative uncertainties for global forest area from 2025 to 2050, floor area increase, and the embodied carbon of constituent materials. For the timber-CLT and bamboo-LVB scenarios, the relatively low global supply capacity

Fig. 5 | The potential reductions in embodied carbon for maximum adoption of each material typology, considering material supply constraints, to supply additional urban housing from 2025 to 2050, for the three carbon accounting approaches. The error bars for the Concrete-BAU reference scenario reflect the inherent uncertainties in estimating the embodied carbon of urban housing demand worldwide to 2050, arising from uncertainties in embodied carbon of constituent materials and the scale of housing demand to 2050. The error bars for the alternative scenarios represent the uncertainties in savings compared to the median values of the Concrete-BAU scenario.



reduces their uncertainty range (as calculated here), within the applied assumptions that no mass afforestation will take place, and existing forests should be managed sustainably in view of competing uses.

The estimated impact of maximum bio-based materials adoption is strongly dependent on the accounting approach: if considering production emissions only, very minor emissions reductions are expected; if using the harvesting-exclusive biogenic carbon method, a combined saving of 2.25 Gt CO_{2(eq.)} is estimated from maximum CLT and LVB together. A previous study estimated that 10% of global demand for concrete could be replaced by CLT, resulting in 5.5 Gt CO_{2(eq.)} savings²; the factor of ~2 difference with this study's estimate is a compound effect of different assumptions for carbon intensity and material intensity. When using the harvesting-inclusive biogenic carbon accounting approach, maximum bio-based material adoption would potentially increase emissions by 4.1 Gt CO_{2(eq.)}. The Concrete-ECO typology is not resource-constrained in the manner of CLT and LVB, and offers substantial carbon savings for an individual housing unit; if low-carbon concrete is fully adopted, the global savings in embodied carbon relative to the benchmark scenario are estimated to be 14.3 Gt CO_{2(eq.)}.

In addition to the resource potential of different materials, an important practical factor is the capacity of their respective sectors to rapidly scale up production over the period of 2025–2050. Current global production capacity and distribution of the key materials were estimated from a range of sources; existing estimates and data were used where available (see “Methods” section). Conventional concrete is currently the most-produced material worldwide (~18 billion m³/year, with other cement-based materials, including mortar, produced in similar volume); SEB, CLT, and LVB have much smaller production volumes in the range of 1.5–3.5 million m³/year. Cement is produced at large-scale factories (typically ~1 Mt/year) at a relatively small number of sites worldwide. Cement is then used to produce concrete: in the context of housing, the majority of concrete is either produced at batching plants and then transported to the site, or bagged cement is used for concrete mixing on-site. Despite being a more recent innovation, limestone calcined clay (LC³) concrete production capacity is already at an estimated 25 million m³/year. The typical production capacity of a single site

and the number of production sites worldwide were estimated for conventional cement, LC³ cement, CLT, and LVB from existing data sources. Typical site production capacity of cement (~1000 kt/year) is over an order of magnitude greater than the typical range for CLT and LVB (10–50 kt/year), which are themselves another order of magnitude greater than for SEB (1–4 kt/year).

If CLT and LVB were to fulfill the feasible maximum proportion of 2025–2050 demand as calculated in this study (12.9% and 0.8% respectively), their production would need to increase by a factor of ~100 (CLT) and ~50 (LVB) compared to current production levels. If SEB were to make the same total contribution (i.e., 13.7%), production would need to increase by a factor of ~200 compared to current levels. The stabilized earth block and engineered bio-material sectors are relatively decentralized, in that the production capacity of an individual site is typically small, but there are a large number of production sites. Hence, a rapid scale-up of global production capacity for SEB, CLT, or LVB would need a rapid increase in site production capacity and/or the number of production sites. Rapid scale-up of material harvesting for CLT and LVB could pose procurement challenges to source sufficient material whilst avoiding exacerbation of existing issues for the world's forests, as highlighted in the previous section.

If low-carbon concrete were in theory to be used to construct all urban housing worldwide, a ~50-fold increase in production of low-carbon concrete compared to current levels would be required. Rapid scale-up would follow a different trajectory to SEB, CLT, and LVB due to the more centralized structure of the industry. LC³, a variety of low-carbon cement, could be scaled up by refurbishing existing cement plants for LC³ cement production, which will then feed into existing supply networks for production of LC³ concrete either at batching plants or on-site. It is assumed that cement plants already in service can shift to producing low-carbon cement with a CAPEX of €6–12 million, in the case of retrofitting an existing rotary kiln to convert from clinker production to calcined clay production⁶³. The scale-up challenges for low-carbon concretes include expanding production networks in areas of growing demand (e.g., Africa).

Beyond logistical factors, economic and social barriers are also key to assessing feasible scale-up rates. For example, the bio-based materials sector

in Northern Europe is the most mature worldwide, yet even in Finland, there are several social barriers (e.g., low sound insulation) and economic barriers (e.g., greater maintenance costs) to timber construction⁶⁴. The global distribution of CLT production is centered in Europe and North America, with only six producers reported in the Southern hemisphere and one in Africa⁶⁵; the majority of research on mass timber is also carried out in Europe and North America⁴⁸. The Eurocentric history and current production of CLT may pose distinct challenges to rapid scale-up in the Global South, where the majority of housing demand is forecast. The promotion of SEBs over the last >50 years provides some useful lessons about the social barriers to adoption of non-conventional materials. Earth-based materials are experiencing a modern renaissance in several Global North countries, yet in the Global South, earthen construction is generally perceived as less desirable than concrete and brick dwellings⁶⁶. SEBs have been adopted by many communities around the world³², and are often promoted in developing countries on their superior durability compared to vernacular adobe blocks, and/or for their lower embodied carbon compared to artisanal fired clay bricks³³. However, attempts by outside actors to increase the adoption of SEBs have often been resisted within those communities⁶⁷, as understanding of local construction contexts has been lacking. Upscaling stabilized earth blocks in the Global South hence faces numerous social barriers as well as financial barriers⁶⁸. The case of SEBs offers a cautionary tale for the barriers that engineered bio-based materials may face. Low-carbon concretes have also faced some social barriers to acceptance, such as the orange-red color of some LC³ concretes. Manufacturing concretes with a reduced cement content has been possible for many years, but barriers to more widespread adoption in practice are insufficient education and incentives for end users⁶⁹. Similarly, concrete codes in Global South countries are largely not yet adapted to a performance-based approach that allows using low-clinker cements or low binder contents (Boumaaza et al.⁷⁰). It is also recognized that regionally specific, vernacular, and regenerative construction practices—tailored to local biomass availability, labor practices, and cultural preferences—may offer more appropriate pathways in many contexts. A truly equitable housing transition will require material strategies that are not only low in carbon but also locally grounded and socially inclusive. In order to make a meaningful contribution to meeting global housing demand, any non-conventional material will need to scale up rapidly: the more decentralized structure of bio-based materials and SEBs poses greater barriers for the rapid scale-up of these sectors.

Discussion

From the material options investigated in this study, there is a huge opportunity to meet global urban housing demand whilst also reducing carbon emissions by improving how we make and use concrete. Low-carbon concrete is a viable option to meet the world's demand for urban housing by 2050, whilst also delivering CO₂(eq.) emissions reductions of up to 14.3 Gt CO₂(eq.) relative to a Concrete-BAU reference scenario over the period 2025–2050. In comparison, maximum adoption of engineered bio-based materials would likely meet up to only 13.7% of demand (within assumed conditions of sustainable harvesting yields and future available forest area), and potentially increase emissions by 4.1 Gt CO₂(eq.) relative to a Concrete-BAU reference scenario. Using an unrealistic harvesting-exclusive accounting methodology, maximum adoption of engineered bio-based materials is estimated to only save ≤2.25 Gt CO₂(eq.) compared to the reference scenario. Uncertainties around embodied carbon and viable resource supply of engineered bio-based materials represent major risk factors to achieving societal goals of decarbonization, adequate housing, and biodiversity conservation, if engineered bio-based materials are planned to be a majority construction material. Considering the evidence presented here around logistical and resource supply aspects, and life cycle assessment of CO₂(eq.), low-carbon concrete is a more realistic option compared to engineered bio-based materials. However, decision-making around materials for housing also depends on social, political, cultural, and economic aspects of sustainability; whilst it was not feasible to investigate these context-dependent dimensions in this study, given its global scope, they

deserve research in context-specific studies. Whilst mass adoption of engineered bio-based materials for structural elements of housing may be possible in some hypothetical future scenarios, under the pragmatic boundary conditions used in this study, such mass adoption appears unlikely to be feasible in practice, certainly it can have very little impact before 2050.

Methods

Data aligned with Shared Socioeconomic Pathways (SSPs) were used wherever possible. This approach helps align with existing integrated approaches to future global development scenarios⁷¹. 2050 was chosen as the end date, as this is widely used as a critical juncture for avoiding catastrophic global warming, e.g., in the Paris Agreement. Whilst a large amount of demand for urban housing is predicted from 2050 to 2100, the uncertainties in all aspects of models are considerably larger in the 2050–2100 time period. Choosing an end date of 2050 reduces the uncertainties in all aspects of the input data for the model.

The definitions of world regions used in this study are:

- Europe: includes mainland Europe, Russia, and the United Kingdom.
- China
- North America
- Latin America: includes Central America, the Caribbean, and South America.
- Middle East & Africa
- Remaining Asia: including India and Australasia

The overall approach to the study was composed of six modules:

1. Developing material typologies
2. Calculating material intensity and resource demand for the different material typologies
3. Estimating the urban housing floor demand
4. Calculating embodied carbon for a single structure of each material typology
5. Estimating feasible resource supply for the key constituent materials
6. Current global production of key materials

Within the mid-rise archetype, a simple grid layout was selected, as this is beneficial for maximizing the material efficiency of the structural frame⁷². The mid-rise archetype consists of four structural components: slabs, columns, non-load-bearing walls, and foundations. There is inconsistency across previous studies as to whether foundations are included. They have been included within the scope of this study, as they form an important and massive part of the structure, and this also reflects better the relative concrete demand across the different material typologies.

Five material typologies were considered:

1. A business-as-usual model (concrete-BAU), with conventional reinforced concrete (RC) foundations, slabs, and columns, and wall infill of fired clay bricks with PC mortar.
2. A low-carbon concrete model (concrete-ECO), with reduced binder content and limestone calcined clay cement (LC³) used in the concrete for the foundations, slabs, and columns, and wall infill of hollow concrete blocks made with LC³, and LC³ mortar.
3. A cross-laminated timber model (timber-CLT), with CLT slabs and walls. Low-carbon (i.e., LC³) concrete is used in the foundations.
4. A laminated veneer bamboo model (bamboo-LVB), with LVB slabs and walls. Low-carbon (i.e., LC³) concrete is used in the foundations.
5. A stabilized earth block model (earth-SEB), with low-carbon (i.e., LC³) concrete used for foundations and slabs, load-bearing walls of SEBs, and wall infill of fired clay bricks with LC³ mortar.

Detailed descriptions of the construction materials used for each structural component within each of the five material typologies (Supplementary Table S2), along with technical descriptions of each construction material used (Supplementary Table S3), are provided in the Supplementary Information.

The “true” global average binder content in concrete is unknown, given that concrete is largely made in a decentralized manner and a large volume of production is in the informal sector. We made a best estimate for the global average binder content that responds to the target strength class characterized for the structural concrete elements designed. The binder content values for each design strength class were selected as an average from a large dataset (>1000 mixes) of more than 120 published case studies globally⁷³.

A stabilizer content of 7% low-carbon cement was specified for the SEB, which is the minimum value required to achieve the target compressive strength for the structural design. A higher quantity of cement stabilizer beyond the reasonable minimum value of 7% would increase the embodied carbon of the SEB. Cement was specified as it is the most commonly used stabilizer for SEB production. The use of alternative, less commonly used stabilizers (e.g., lime, bio-stabilizers) would also affect the embodied carbon of SEB.

The scope of this study is limited to the materials used for structural elements and infill walls. Only timber and bamboo could make a meaningful contribution towards demand for structural materials at a global scale by 2050. Similarly, whilst whole timber and full culm bamboo construction is possible, only the engineered forms of timber and bamboo were included in this study, given their advantages in terms of predictable engineering properties and compliance with existing building codes^{74–78}. However, there is potential for bio-based materials to be used in non-structural applications, such as thermal and acoustic insulation, wall panels, and interior finishes. These uses could provide carbon storage and operational energy savings through improved building performance (Peñaloza et al.⁷⁹ Pittau et al.⁸⁰ Robati et al.⁷⁷). Several studies have shown that natural-fiber insulation (e.g., hemp, flax, cellulose, mycelium) can achieve negative embodied carbon when accounting for biogenic storage and avoided emissions from conventional materials (Melià et al.⁷⁸; Bribián et al.⁷⁴). While detailed evaluation of such applications lies outside the scope of this work, they represent an important complementary pathway for carbon mitigation in the built environment and merit further investigation.

For the material intensity calculations (i.e., the mass of material per unit area of floor space), only structural elements were included, namely the slabs, columns, load-bearing walls, non-load-bearing walls, and foundations. Building envelope materials (e.g., insulation, windows) were excluded. While infill walls are commonly classified as non-structural elements, there are two reasons we had to include them in the studied boundary. First, masonry infills have been demonstrated to contribute to lateral load resistance (Dias-Oliveira et al.⁸¹), which allows for a like-for-like comparison between the two different systems being studied (a reinforced concrete skeleton vs load-bearing bio-based materials). Second, by including infill walls, in addition to the structural elements, the materials considered constitute 80–90% of the total embodied carbon of typical urban housing buildings (Röck et al.⁸²).

For each of the five material typologies, a structural design was done based on the EN 1992-1-2. The structural analysis was carried out using the SAP2000 software package based on the minimum superimposed loads and self-weights as per the load combinations in the code and literature-based material properties with safety factors from EuroCode 2 (EN 1992-1:2004-1) for concrete structures, as well as EuroCodes 5 and 6 for timber and masonry structures⁸³. The soil was assumed to have a bearing capacity of 250 kN/m², typical of cohesive sand-clay mixtures, and the foundation systems were chosen according to the structure type (isolated footings for RC skeleton and strip footings for load-bearing structures). The input parameters for each building component were designed to satisfy the target structural requirement values and are summarized in Supplementary Table S4.

The term construction materials will hereafter be used to refer to the specific materials used in the different material typologies (e.g., Reinforced PC concrete, CLT, LC³ mortar). The term constituent materials will hereafter be used to refer to the individual material inputs that are contained within those construction materials (e.g., clinker, bamboo, coarse

aggregate). From the model, the material intensity of the different construction materials was calculated for each of the five material typologies. The total material intensity values were lowest for the timber-CLT (428.6 kgm⁻²) and bamboo-LVB (519.8 kgm⁻²) typologies, attributed to the low density of the CLT and LVB used for walls and slabs. The highest total material intensity value was for the earth-SEB typology (1805.0 kgm⁻²). The two concrete scenarios lie in the middle of this range (1093.3 kgm⁻² for “business as usual” concrete and 1030.7 kgm⁻² for low-carbon concrete). A wide range of values exist in the literature for material intensity. The material intensity of 229 kgm⁻² for CLT within the timber-CLT typology sits within the range of previous values for CLT of 180 kgm⁻²¹² and 280 kgm⁻²⁸⁴.

The breakdown of each of the material intensity values into building components is provided in Supplementary Tables S1 and S5. The concrete material intensity values for the timber-CLT and bamboo-LVB archetypes are below the lower quartile since, in this design, concrete is considered to be used only in the foundations, while in other designs, concrete would also be used for slabs and shear walls. Similarly, the material intensity value for wood in the timber-CLT archetype is above the upper quartile since the building is designed where all superstructure components (slabs, load-bearing, and non-load-bearing walls) are made out of timber.

The dynamic model of Deetman et al.⁸⁵ was used, based on the SSP2 (median) scenario, which calculated annual urban residential floor area additions for the 26 regions defined within the IMAGE model. This model covers gross additions, including new housing to replace end-of-life housing. The gross floor area addition from 2025 to 2050 was then calculated by summing the annual additions over this time period. To estimate an upper and lower bound for floor area increase, the net change in regional stocks per year was adopted from ref. 86, and the gross floor addition was adjusted based on the baseline projections for the SSP2 scenario.

Operational impacts, as well as maintenance and repair, were excluded from this study’s scope. A time horizon of 50 years was selected for the extended life cycle analysis of the buildings under study. End-of-life emissions (i.e., C1–C4) were generally excluded from calculations due to the uncertainty of modeling end-of-life routes for housing worldwide into the future. An exception is in the harvesting-exclusive biogenic carbon accounting, which implicitly assumes that incineration of biomass construction products occurs at the end of life and uses the building lifetime as part of calculations to estimate the net sequestration effect.

Global Warming Potential (CO_{2(eq.)}) inventory values were obtained from a range of previous studies for each of the constituent materials, to calculate production emission (i.e., A1–A3). A summary of the inventory data used for the LCA calculations is shown in Supplementary Table S6, while the background database is shown in Supplementary Table S7. The selected LCA papers constituting the background database relied primarily on primary data for their LCA calculations.

Sequestration potential per unit volume of bio-based material product was calculated using the GWP_{bio} semi-static method described by Pittau et al.³⁸ (Eq. 1). This approach bridges the (timing element) gap between the IPCC static characterization values and the highly complex dynamic approach³⁸. The key assumptions are: trees are replanted after harvesting; the rate of carbon uptake in forests is constant from the early stage of growth to the final clear-cut, and biogenic residues are excluded from consideration. Density values used were 500 kgm⁻³ for CLT⁸⁷ and 700 kgm⁻³ for LVB⁸⁸. The carbon content value was assumed to be 50 wt.% in line with the dry mass of forest products³⁸; the mass ratio between 1 mole of CO₂ and 1 mole of C is 3.67.

Equation 1: Semi-static sequestration model for bio-based materials. SCO₂ = sequestration potential; ρ₀ = bulk density; CC = carbon content (wt.%); r_{CO₂:C} = mass ratio between 1 mole of CO₂ and 1 mole of C.

$$S_{CO_2} = \rho_0 \cdot CC \cdot r_{CO_2:C} \quad (1)$$

Once the carbon sequestration potential per unit volume of bio-based material product was calculated, the GWP sequestration per unit volume over the 50-year time horizon was then calculated, taking into account the

influence of building service life and forest rotation period (Eq. 2). A service life for the housing unit of 50 years was assumed. The rotation cycle duration for bamboo was chosen to be 5 years—this is a typical maturity duration for harvesting across several species of bamboo used for construction products^{58,89}. For timber, the rotation cycle was chosen to be 30 years. Based on these values for service life and rotation cycle duration, the coefficients for GWP_{bio} were estimated at 0.18 and 0.08 for CLT and LVB, respectively, from the values listed in Pittau et al.³⁸. This approach assumes that the carbon is regenerated in the forest after the construction.

Equation 2: Global warming potential uptake model for bio-based materials, considering service life and rotation cycle duration. GWP_{bio} = Global Warming Potential value per kg of CO₂ sequestered in a bio-based material product; SCO_2 = sequestration potential.

$$GWP_{uptake(2025-2050)} = GWP_{bio} \cdot SCO_2 \quad (2)$$

This approach is an overestimate of the sequestration capacity, since it assumes that all the buildings constructed over the 2025–2050 period will be constructed in 2025, not as a linear increment. An average value was then used, from the value calculated from the semi-static approach and literature values for sequestration associated with CLT^{37,87} and LVB^{37,43}. The values obtained from each model were then complemented with literature data from references with similar model assumptions for higher statistical accuracy.

The carbon sequestration values were then summed with the production emissions to obtain values via the harvesting-exclusive biogenic carbon accounting approach for the bio-based material typologies for the CLT and LVB in the CLT-Timber and LVB-Bamboo material typologies.

We used the global forest carbon model (CHARM) as described in Peng et al.³⁹ to estimate forest carbon emissions from deforestation and forest degradation due to wood harvesting. CHARM takes wood consumption by country as inputs and translates these demands into wood supply needs from plantations and secondary forests. Wood supply is categorized into wood fuel and industrial roundwood; the latter is further split into three groups by their life cycles: long-lived products such as sawnwood and panels, short-lived products such as paper, and very-short-lived products such as the manufacturing waste for energy recovery. The wood product shares in 2025 are predicted through the relationship between historical wood consumption from FAOSTAT⁹⁰ and income levels. We ran CHARM under a scenario where secondary forests regrow for 25 years after harvesting, resulting in global annualized carbon costs in MtC (2025–2050). Model simulations were carried out under a total roundwood demand level, and the carbon costs for industrial roundwood were then calculated based on its wood demand share to the total roundwood. The carbon costs take into account the forest carbon loss due to harvests and wood products storage benefits, and more importantly, they measure forest carbon dynamics by comparing forest re-growth after harvests to continuous growth without harvests. It was assumed that the market share of harvested bamboo for industrial products (26%) is similar to that of timber. Also, it is established that the biomass ratio (1:2) of culm to root in bamboo⁵⁸ is similar to the ratio of harvested roundwood to root in timber³⁹. The harvesting cost per unit volume of harvested bamboo was estimated by applying a pro-rata adjustment to the timber value, to account for the higher density of bamboo (a value of 700 kgm⁻³ was used)⁸⁸ compared to timber (a value of 500 kgm⁻³ was used⁸⁷).

The harvesting cost of a cubic meter of CLT was then estimated by multiplying the harvesting emissions (600 kg CO_{2(eq.)}/m³) for the volume of harvested roundwood timber needed to manufacture one cubic meter of CLT timber (3.23 m³) by the industrial process yield factor (0.31). This assumes a mass allocation for uses of all factory offcuts, which is an optimistic assumption for CLT production. As a result, the harvesting cost per unit of volume of CLT product is the same as the harvesting cost per unit of harvested timber. The same approach was also applied to LVB.

The carbon costs associated with harvesting were then summed with the values from production emissions and carbon sequestration, to obtain

values via the harvesting-inclusive carbon accounting approach for the CLT and LVB in the CLT-Timber and LVB-Bamboo material typologies.

Displacement (or substitution) factors in Table 1 were calculated using the most widely used approach, i.e., using units of tonnes of carbon for both greenhouse gas emissions and the content⁴⁷ (Eq. 3). The scope of comparison was the sum of structural materials used for each material typology, consistent with the previous embodied carbon calculations. The two bio-based material typologies used were CLT-Timber and LVB-Bamboo; the two non-bio-based reference material typologies used were concrete-BAU and concrete-ECO.

Equation 3: $GHG_{non-bio}$ = greenhouse gas emissions associated with a non-bio-based reference material typology; GHG_{bio} = greenhouse gas emissions associated with a bio-based material typology; BU_{bio} = amounts of bio-based materials used in a bio-based material typology; $BU_{non-bio}$ = amounts of bio-based materials used in a non-bio-based reference material typology. Adapted from Sathre and O'Connor⁴⁷.

$$Displacement\ Factor = \frac{GHG_{non-bio} - GHG_{bio}}{BU_{bio} - BU_{non-bio}} \quad (3)$$

Carbon sequestration of cementitious materials (concrete and mortar) was modeled using the semi-static approach described by Pittau et al.³⁸ (Eq. 4). The degree of carbonation was assumed as 0.7, according to Pittau et al.³⁸; the values used for carbon sequestration potential were 0.165 kg CO₂kg⁻¹ for the BAU concrete⁹¹ and 0.066 kg CO₂kg⁻¹ for the low-carbon concrete⁹²; the average fraction of carbonated concrete per unit volume of concrete was estimated via the volume of carbonated material for a carbonated cover depth over a 50-year period, averaged across the XC2 and XC3 exposure classes, over a unit area of exposed concrete surface. Any necessary adjustment for the concrete cover of the low-clinker concrete mix in concrete-ECO for the higher carbonation rate was ignored due to its minimal (<2%) impact on the concrete volumes on the building level, according to Hafez et al.⁹³.

Equation 4: Semi-static carbonation model for concrete and mortar. C_s = mass of carbonated CO₂ per unit volume of concrete (kg CO₂m⁻³); ϕ = degree of carbonation in carbonated regions (%); C_m = carbon sequestration potential per unit mass of binder (kg CO₂kg⁻¹); V_c = average fraction of concrete volume that has carbonated (vol.%); m_b = mass of binder per unit volume of concrete (kgm⁻³).

$$C_s = \phi \cdot C_m \cdot V_c \cdot m_b \quad (4)$$

The carbon sequestration potential of the binders in the concrete-BAU and concrete-ECO scenarios was estimated using Eq. 5³⁸. The SCM content in each binder was specified as 20 wt.% in CEM II (concrete-BAU scenario) and 45 wt.% in LC³ (concrete-ECO scenario).

Equation 5: Carbon sequestration potential of binder. C_m = carbon sequestration potential per unit mass of binder (kg CO₂kg⁻¹); α = carbon sequestration potential of clinker (kg CO₂kg⁻¹); β = scaling factor; γ = wt.% of SCM in the binder.

$$C_m = \alpha - (\beta \cdot \gamma) \quad (5)$$

The uncertainties for the values of embodied carbon per unit floor area in Fig. 2 were calculated based on uncertainties in the embodied carbon of the constituent materials. Literature values were compiled for the cradle-to-gate carbon emissions of each of the constituent materials (Tables S5 and S6 in the Supplementary Information). Values for “mean average ±1 standard deviation” were then used as maximum/minimum values for embodied carbon on the individual constituents, which were then used to obtain a maximum/minimum value for embodied carbon per unit floor area for the whole building.

For the bio-based typologies Timber-CLT and Bamboo-LVB, uncertainties calculated for production emissions, and then carried through to the “harvesting-exclusive” and harvesting-inclusive’ accounting approaches, as

the additional emissions arising from sequestration and harvesting are a simple sum on top of the production emissions.

Estimates of available timber and bamboo for CLT and LVB production were made by first calculating forest areas, and then calculating the viable quantities that could be harvested per year without excessive damage to forest ecosystems. This is the same approach used by Pomponi et al.²⁴. Mishra et al.¹⁰ used the MAgPIE 4 (Model of Agricultural Production and its Impact on the Environment) modeling platform to project quantities of harvestable forest; this dynamic approach is more detailed, but has the disadvantage of being less obvious what the underlying assumptions and drivers are. For this study, a static modeling approach based on forest area was deemed most appropriate.

Total forest area was obtained from the IMAGE 3.2 platform values for total global forest area in 2025⁵⁰, which itself is based on United Nations Food and Agriculture Organization⁹⁴ source data. The total forest area value of 4.04 billion is based on World Bank data²⁴ for timber and based on Kuehl et al.⁹⁵ for bamboo. Large-scale coordinated increases in plantation areas, as explored by Mishra et al.¹⁰ were not explored as these scenarios require large-scale coordinated action, which is less relevant for the 2050 time horizon compared to the 2100 one used by Mishra et al.

The potential to meet urban housing demand over the 2025–2050 period with the timber-CLT and bamboo-LVB material typologies was calculated for major world regions, using the projected urban floor area additions and the feasible supply of the respective bio-based materials.

The feasible annual supply of timber for CLT was estimated by applying various scaling factors. We apply a 30% limit on forest area available for harvesting, aligned with FAO FRA estimates that production forests account for roughly 28–30% of global forest area (FAO, 2024). The remaining forest area is treated as set aside for biodiversity, protection, and other social functions. This is a simplification, as it does not consider plantation forest and generic forestry areas as distinct, which have different harvesting rates; however, given plantation area currently makes up a very small proportion of world forest area, this approximation is reasonable.

A representative global value for sustainable annual yield was calculated from the mean average of various sources directly reporting sustainable annual yield for different forests^{96–98}. Multiplying the sustainable annual yield by the forest area available for timber harvesting gave an estimate of sustainable annual timber harvest of 3.51 billion m³/year. Summing over the period of 2025–2050 gave a total sustainable timber harvest of 87.75 billion m³. The timber harvest is used for numerous applications (e.g., pulp and paper, fuel, furniture); current estimates are that only 26.4% of cut timber is used in lumber and veneers³⁹. Exploring the extent to which timber can be replaced or substituted in other applications is beyond the scope of this study, so it was assumed that the proportion of use in lumber and veneers will stay constant over time. Therefore, it was estimated that 0.93 billion m³/year of timber would be available for engineered wood products, summing to 23.17 billion m³ over the period of 2025–2050.

The CLT manufacturing process involves losses; it is estimated that 31% of timber input (in the form of cut logs) in the CLT production process ends as CLT (Nakano et al.⁸⁷). Using this factor, the potential sustainable production of CLT was estimated as 0.29 billion m³/year, summing to 7.18 billion m³ over the period of 2025–2050. This excludes limitations of CLT processing capacity, which are evaluated in the Results section of the article.

The total area of bamboo forests worldwide is estimated to be 40 million ha⁹⁵. The proportion of total forest area available for bamboo harvesting, out of the total forest area worldwide, was assumed to be 30%, based on FAO data⁹⁴. Other forest area is treated as set aside to fulfill biodiversity and social functions. For bamboo forests, a sustainable annual harvesting rate has been recommended as 9.5 m³/ha/year⁵⁸. Multiplying the sustainable annual harvesting rate by the forest area available for bamboo harvesting gave an estimate of sustainable annual bamboo harvest of 0.11 billion m³/year. Summing over the period of 2025–2050 gave a total sustainable bamboo harvest of 2.85 billion m³. The bamboo harvest is used for numerous applications (e.g., kitchen

equipment, furniture). The proportion of bamboo currently used in construction and veneer products was assumed to be the same as for timber at 26.4%³⁹. The LVB manufacturing process also involves losses; it is estimated that 59% of the bamboo input (in the form of full culms) in the LVB production process ends as LVB⁹⁹. Using this factor, the potential sustainable production of LVB was estimated as 17.76 million m³/year, summing to 443.9 million m³ over the period of 2025–2050. This excludes limitations of LVB processing capacity, which are discussed in the “Discussion” section of the article.

The two input materials in SEBs are sub-soil and cement. Whilst sub-soil can be considered globally abundant, for on-site production of SEBs in urban areas, sub-soil is not necessarily always locally available. Nonetheless, SEB production was not considered to be resource-limited on the global scale. This excludes limitations of SEB production capacity, which are discussed in the “Discussion” section of the article.

Global concrete production is estimated as 40 Gt/year¹⁰⁰, of which the overwhelming majority is conventional concrete made using Portland clinker-based cement (PC). Some modest global expansion of production is expected in some regions to meet demand to 2050. The primary raw materials of clay, shale, limestone, and gypsum are considered abundant at the global scale, although some regions face issues with the location and quality of deposits. Therefore, PC was considered abundant for the purposes of this study.

The sustainability of aggregate extraction has received increased scrutiny in recent years, regarding the impacts of extraction on aquatic ecosystems, particularly arising from illegal extraction⁶². Nonetheless, on a global level, the supply of aggregates is considered to be abundant for the purposes of this study.

Clays are considered to be globally abundant, although not all clays are suitable for the production of calcined clays within LC³ systems under their current design. Nonetheless, calcined clays were considered globally abundant for the purposes of this study. This excludes limitations of calcined clay production capacity, which are discussed in the “Results” section of the article.

Figure 5 presents estimates for net carbon emissions up to 2050, for different scenarios of material adoption in urban housing worldwide. The benchmark scenario is “Concrete-BAU,” against which alternative scenarios are compared in terms of their savings or additional emissions. The carbon emissions associated with each alternative scenario are estimated based on:

- a material typology (Concrete-ECO, Timber-CLT, or Bamboo-LVB)
- the maximum housing demand that each material typology can feasibly meet (based on the estimations of Section)
- the choice of carbon accounting method (production emissions only, production emissions plus harvesting-exclusive biogenic carbon emissions, or production emissions plus harvesting-inclusive biogenic carbon emissions).

The error bars for the Concrete-BAU reference scenario reflect the inherent uncertainties in estimating the embodied carbon of urban housing demand worldwide to 2050, arising from uncertainties in embodied carbon of constituent materials and the scale of housing demand to 2050. The upper bound Concrete-BAU scenario corresponds to embodied carbon values of “mean average + 1 standard deviation” obtained from literature, for an upper estimate of housing floor area demand for 2050. The lower bound Concrete-BAU scenario corresponds to embodied carbon values of “mean average – 1 standard deviation” obtained from literature, for a lower estimate of housing floor area demand for 2050. The upper and lower bounds for floor area increase were estimated by firstly obtaining the relative difference in upper/lower scenarios from Güneralp et al.⁸⁶, and then applying it to the median gross floor addition projections for the SSP2 scenario.

The error bars for the alternative scenarios represent the uncertainties in savings compared to the median values of the Concrete-BAU scenario (rather than the upper or lower bounds of the Concrete-BAU scenario). Their error bars reflect underlying uncertainties in the proportion of housing demand that could feasibly be met by each material typology, and in

the embodied carbon of the constituent materials. The upper and lower bounds for each alternative scenario were calculated based on a maximum/minimum set of values for each. These values were calculated in two parts:

(1) Uncertainty in the proportion of floor area demand met by alternative material typology.

This uncertainty applies to the bio-based alternative scenarios (i.e., Timber-CLT and Bamboo-LVB), and is a function of global forest area and urban housing demand worldwide to 2050. The lower bound value is calculated using the lower bound value for forest area and forecasted floor area increase; the upper bound value is calculated using the upper bound value for forest area and floor area increase. For the global forest area, all values were obtained from the IMAGE 3.2 dataset⁵⁰, and for each scenario, a midpoint value was taken between forest area values for 2025 and 2050. The median value corresponds to SSP2, the lower bound value corresponds to SSP3, and the upper bound value corresponds to SSP1. The upper and lower bounds for floor area increase were estimated by firstly obtaining the relative difference in upper/lower scenarios from Güneralp et al.⁸⁶, and then applying it to the median gross floor addition projections for the SSP2 scenario.

(2) Uncertainty in the embodied carbon of constituent materials

The lower and upper bound values for embodied carbon per unit floor area, for each material typology, were calculated using the same approach used for the single structure assessment. Literature values were compiled for the cradle-to-gate carbon emissions of each of the constituent materials (Tables S5 and S6 in the Supplementary Information), and the ± 1 standard deviation range was then applied as a maximum/minimum scenario, which followed through to the building level. The potential emissions savings (or additional emissions) for each alternative scenario in relation to the Concrete-BAU scenario were then calculated based on comparison to the emissions associated with the equivalent floor area built using the Concrete-BAU typology.

Current worldwide cement production was taken from Global Cement and Concrete Association data¹⁰¹, and typical production capacity per site was based on Van Oss and Padovani¹⁰². LC³ production was estimated based on a current known production capacity of calcined clay for cements of 2.5 Mt/year¹⁰³. Assuming a cement formulation of 30 wt.% calcined clay, and an average binder content of 308 kg/m³ for low-carbon concrete as used throughout, a conservative estimate of low-carbon production is 25 Mm³/year. CLT worldwide production capacity and typical production capacity per site were based on numbers presented by De Araujo and Christoforo⁶⁵. No information on worldwide LVB production was available—worldwide capacity and typical production capacity per site were based principally on information about the Chinese LVB sector¹⁰⁴. No information on worldwide LVB production was available—values for worldwide production were extrapolated from data about the Argentinian SEB sector¹⁰⁵.

Data availability

The dataset is available online at <https://doi.org/10.5281/zenodo.17711172>.

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Author contributions

Conceptualization (H.H. and K.S.); data curation (H.H. and A.T.M.); formal analysis (H.H. and A.T.M.); methodology (H.H., A.T.M., and L.P.); project administration (K.S.); supervision (K.S.); visualization (M.F. and A.T.M.); writing—original draft preparation (H.H. and A.T.M.); writing—review and editing (H.H., A.T.M., M.F., L.P., and K.S.).

Competing interests

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Additional information

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