Buildings as a global carbon sink

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The anticipated growth and urbanization of the global population over the next several decades will create a vast demand for the construction of new housing, commercial buildings and accompanying infrastructure. The production of cement, steel and other building materials associated with this wave of construction will become a major source of greenhouse gas emissions. Might it be possible to transform this potential threat to the global climate system into a powerful means to mitigate climate change? To answer this provocative question, we explore the potential of mid-rise urban buildings designed with engineered timber to provide long-term storage of carbon and to avoid the carbon-intensive production of mineral-based construction materials.

During the Carboniferous period, giant fern-like woody plants grew in vast swamps spread across the Earth's surface. As successions of these plants grew and then toppled, they accumulated as an increasingly dense mat of fallen plant matter. Some studies have suggested that this material resisted decay because microbes that would decompose dead wood were not yet present[1], while others have argued that a combination of climate and tectonics buried the dead wood and prevented its decomposition[2]. Over millions of years, geological pressures and temperatures transformed that accretion of organic matter into fossil fuel deposits (Fig. 1, left panel). Since the advent of the industrial revolution in the mid-nineteenth century, these deposits have been continuously extracted and burned to fuel the industrialization required to meet the demands for products and infrastructure of a burgeoning population, leading to substantial increases in atmospheric concentrations of carbon dioxide (CO_2) (Fig. 1, middle panel).

High atmospheric CO_2 concentrations, longer growing seasons, warmer temperatures, forest regrowth and increasing nitrogen mineralization have been identified as the main drivers of current increases in the productivity of vegetation globally[3–5]. In recent decades, the world's forests have served as a net sink of carbon (1.1 ± 0.8 GtC yr^{-1}) with living tree biomass accumulating most of it[6]. While local[7] and global[8] studies suggest that climate change will likely enhance forest growth in the future, it remains unclear how long CO_2 fertilization effects, especially in nitrogen-limited forests, will persist[9] and continue mitigating climate change. Enhanced carbon sequestration in forests may be reinforced, counteracted or even offset by concurrent changes in surface albedo, land-surface roughness, emissions of biogenic volatile organic compounds, transpiration and sensible heat flux[10]. Moreover, storing carbon in forests over the long term becomes less reliable because of the changing dynamics of forest disturbances such as fire, wind and insect outbreaks, which are closely linked to climate change[11,12] and can decrease forest growth and storage of carbon in forests[13]. For example, droughts and frequent heat waves have been shown to reduce forest productivity and net carbon uptake[14,15].

The organic deposits of modern forests will not accumulate in large quantities underground as in the Carboniferous period, nor replenish the underground carbon pool naturally because soil microorganisms, plant species and Earth's climate have inevitably evolved. Furthermore, current rates of fossil fuels combustion have far exceeded carbon sequestration rates in forests creating the need for national governments to submit reduction targets for CO_2 emissions to the United Nations Framework Convention on Climate Change (UNFCCC) as part of their obligations under the Paris Agreement[16]. However, even if all governments were to achieve their commitments, anthropogenic CO_2 emissions would exceed the carbon budget range associated with the agreement[17]. The mitigation pathways presented by the Intergovernmental Panel on Climate Change (IPCC)[18] try to account for this dilemma by introducing large-scale carbon extraction schemes, mainly based on bioenergy with carbon capture and storage, which are supposed to reconcile the budget. These schemes convert biomass to heat, electricity, or liquid or gas fuels and couple that activity with storing the CO_2 on land or in the ocean. Such an approach poses socio–economic risks[19] and threats to natural ecosystems[20,21].

Barring global-scale disasters of natural and human-caused origin, the coming decades will be characterized by demographic and economic growth in many parts of our planet. This will result in accelerated urbanization—UN projections foresee 2.3 billion new urban dwellers by 2050[22]—and entails the production of an enormous volume of housing and infrastructure. We propose to exploit this projected demand for urban buildings as a means to mitigate climate change. By employing bio-based materials, technologies and construction assemblies with high carbon storage capacity and low embodied carbon emissions, we can create a durable, human-made global carbon pool while simultaneously reducing CO_2 emissions associated with building sector activities (Fig. 1, right panel). Embodied energy or carbon emissions refer to energy or emissions associated with building construction, including extracting, transporting and manufacturing materials.

The problem

A recent study concluded that if the global population increases to 9.3 billion by 2050[23], then the emissions from the development of new infrastructure could claim 35–60% of a remaining carbon budget[24] based on limiting a global temperature increase to 2 °C. Further reductions in the energy demands and associated greenhouse gas emissions associated with the manufacture of mineral-based construction materials will be challenging, as these industries have already optimized their production processes. Future improvements in energy efficiency

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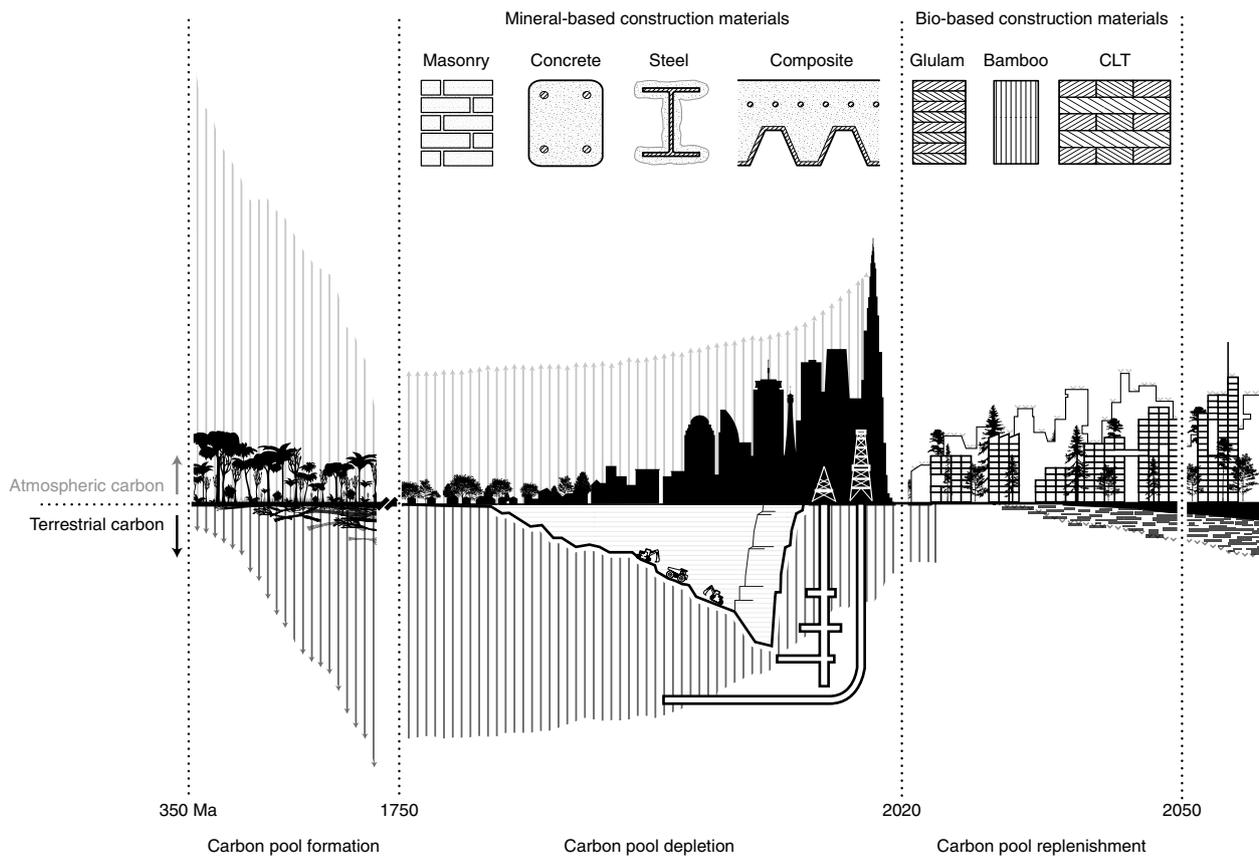
Fig. 1 | Processes responsible for formation, depletion and potential replenishment of land carbon pool and changes in atmospheric CO₂ concentrations over time. Left panel: over millions of years the carbon pool on land was formed and CO₂ concentrations in the atmosphere slowly declined because of various processes including organic carbon burial, rock weathering and so on. Middle panel: urban and industrial growth prompted by the industrial revolution have gradually depleted land-based carbon pools and increased atmospheric CO₂ concentrations. High-reaching and heavy-load-bearing urban buildings constructed from concrete and steel, produced with raw materials and fuels extracted from ever deeper layers of the Earth's crust, were intensive in both energy consumption and greenhouse gas emissions. Right panel: cities built from bio-based materials such as engineered timber and bamboo can serve as constructed carbon sinks. Storing and maintaining carbon in these densely constructed carbon pools will help replenish the terrestrial carbon storage, thereby reducing current atmospheric CO₂ levels and offsetting future emissions. Ma, million years ago.

per ton of material are thought to be limited to 24% for steel and 13% for cement[24], which dominate materials energy use worldwide[25]. Replacing fossil fuels by renewable energy sources will never reduce CO₂ emissions from steel and cement manufacture to zero because of emissions that emanate from associated chemical reactions[26]: calcination in cement production and use of coke from coking coal to reduce iron oxide in steel production. In 2014 these represented 1,320 MtCO₂ for cement and 1,740 MtCO₂ for steel[26]. For cement production, about 60% of the total emissions[27] stem from calcination with some of it recaptured slowly through the subsequent carbonation of exposed surfaces of concrete structures and waste[28].

The buildings and construction sector currently accounts for about half of all global steel demand[29]. The associated energy demand in steel production could be reduced by 60 to 95%[30] by using secondary rather than primary raw materials. The supply of secondary materials is however limited to 30 to 40% of primary input[31] because of the several-decade time lag between metal products' first use and the end of their useful life[32]. The end-of-life recycling rate of steel in construction is at 85% with expected efficiency gains of up to 90% by 2050[32]. Further efficiency gains in steel recycling will not change the magnitude of available old scrap if the steel demand continues to grow over the same period[33].

Contemporary construction across the world has two additional poorly researched yet relevant impacts on the carbon cycle: first, the

production of cement, concrete, asphalt, glass and so on requires vast amounts of sand extracted from beaches, rivers and seafloors; second, mining can lead to extensive local deforestation. The sand mining not only exerts substantial pressure on available deposits, which have become an increasingly scarce global resource, but also compromises the carbon uptake capacity of the aquatic ecosystems disturbed during extraction[34]. Together, the mining infrastructures and the development of mineral commodity supply chains are responsible for a disproportionate loss of forests surrounding mines and resulting loss of stored carbon. Mining-induced deforestation in Brazil alone was responsible for 9% of all Amazon forest loss in 2005–2015: twelve-times more than the area deforested within permitted mining leases[35].

Therefore, the demand by the contemporary global building sector for construction materials will remain a major source of greenhouse gas emissions unless appropriately addressed. Buildings, which are designed to stay for decades, are an overlooked opportunity for long-term storage of carbon, because the most-widely used construction materials such as steel and concrete hardly store any carbon (Fig. 2).

Bio-based materials in construction as a solution
The use of roundwood (logs) or solid sawn or shaped timbers was part of a long, preindustrial history of buildings. Although the
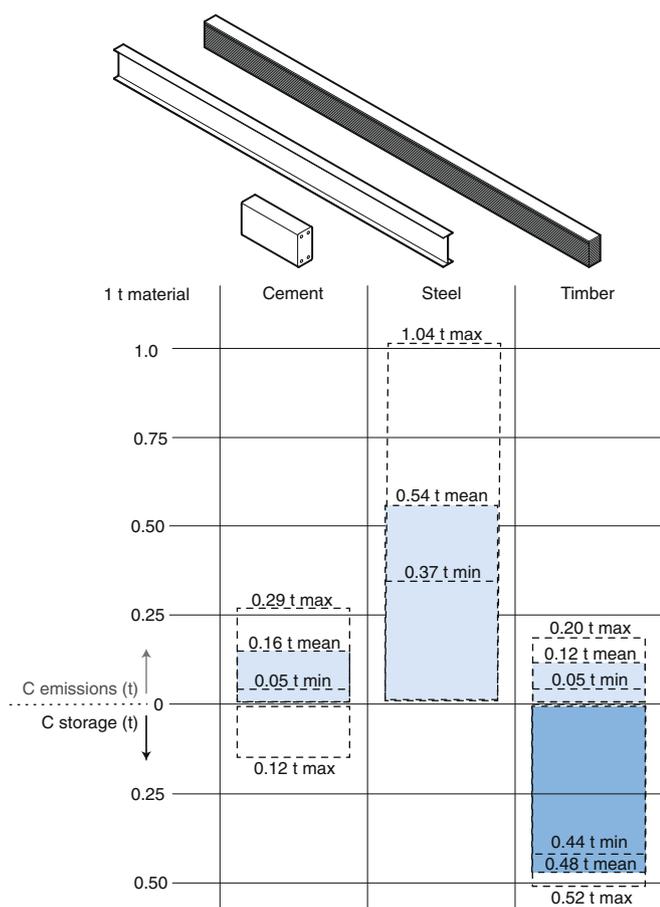
Fig. 2 | Physical dimensions, carbon emissions and carbon storage capacity of 1 t of cement, steel and timber materials. Mineral-based materials have substantial embodied carbon emissions with minimal carbon storage capacities, while timber stores a considerable quantity of carbon with a relatively small ratio of carbon emissions to material volume. The displayed carbon storage of cement is the theoretical maximum value, which may be achieved after hundreds of years. The carbon storage of steel is not displayed as it is only 0.004 tC t⁻¹ steel. See the Supplementary Information for a detailed explanation of the calculations underlying these estimates.

structural applications of wood continue today, primarily in the form of light-frame construction associated with low-rise residential buildings, the use of heavy solid timber for industrial and commercial multi-storey buildings waned during the late nineteenth and twentieth centuries. Steel and reinforced concrete technologies and construction techniques became more refined, and the fossil fuels that supplied manufacturing energy for heat-intensive production processes became cheaper and more plentiful. In spite of relatively lower extraction and processing energies, a host of other factors has limited the contemporary use of solid wood in all but low-rise suburban and rural buildings. In the modern age of large-scale commercial construction, in which an increasingly standardized engineering profession sought uniformity and predictability in its structural material, wood's inherent heterogeneity became a liability. The anisotropic strength characteristics created by wood's grain structure, its hygroscopic absorption and desorption of water vapour, and its expansion and contraction with swings in ambient humidity, were seen as material defects. Variability in the properties and processing requirements of different wood species[36,37] created additional barriers to wood application in contemporary

structural design. Although the fire-resistive, charring properties of large structural timbers are recognized in most international building codes, the prevalence of fires in light-frame wood buildings has fostered the popular association of timber construction with catastrophic urban conflagration. No material is inherently better at withstanding exposure to fire or potential catastrophic seismic or weather-related events. Buildings are systems of materials and connections that must be comprehensively engineered to address estimates of stresses. Structural steel is extremely strong, but is subject to corrosion/oxidation when exposed to air- or water-borne acids or to plastic failure when exposed to fire. Concrete has high compressive strength, but little tensile capacity and so must be hybridized in structural applications to include reinforcing steel as a tensile element to protect it from tensile failures. That reinforcing steel, in turn, must be carefully engineered and placed relative to the surface of the concrete structural member to avoid corrosion or failure in fire conditions. Wood is combustible, but in large sections forms a self-protective charring layer when exposed to fire. It must therefore be sized to anticipate a potential charring layer that will protect the remaining 'cold wood' core to provide building structure under-extended fire loads. Building failure, as is aptly demonstrated historically, is due to system engineering failure first, and then material failure.

Mass timber refers to engineered wood products that are laminated from smaller boards or lamella into larger structural components such as glue-laminated (glulam) beams or cross-laminated timber (CLT) panels. Methods of mass-timber production that include finger-jointing, longitudinal and transverse lamination with both liquid adhesive and mechanical fasteners have allowed for the re-formulation of large structural timbers. These new approaches address the natural inconsistencies of wood and make its mechanical performance in large structural members more predictable[38]. Smaller boards or lamellae, easily inspected, graded, and with defects identified and removed, can be distributed throughout a structural cross section based on strength characteristics and specific load-bearing requirements. This approach optimizes both the manufacturing yield from harvested wood fibre and the strength of the structural components. As with other materials, the fire-safety of timber buildings depends on several factors, including foremost the building's design with regard to the behaviour of fire, the management of fire-safety systems and egress routes during evacuation, and the appropriate application of fire-resistive material[39,40]. Extensive international fire testing of glue-laminated beams and CLT structures has demonstrated fire resistance in buildings up to 18-storeys tall. Records for floor area, the length of structural spans and the height in timber buildings are exceeded with increasing frequency[41]. The recent emergence of these 'mass timber' technologies and the technical research and regulatory revisions that underpin it[38,42] demonstrate that engineered timber products and structural systems offer a potential substitute for much of the mineral-based materials in urban building construction. Numerous case studies have emphasized the environmental benefits of bio-based materials such as wood and bamboo in construction at different spatial scales: from a single building[43], to a city district[42], to a region[44–47], and to the planet[48,49].

Our analysis considers the broad-based adoption of engineered timber structures and their potential global substitution for steel and concrete in mid-rise structural systems. We focus on primary structure bearing aboveground gravitational and lateral load (Extended Data Fig. 1) and enclosure of buildings in mid-rise urban construction (4–12 storeys). Foundation systems are not included for the reason that reinforced concrete or masonry will remain the predominant material approach for below-grade structural components for the foreseeable future. We have chosen to analyse structural assemblies common to mid-rise urban residential and commercial buildings in order to compare a building scale and type

that is demonstrably amenable to the material substitution we propose (see Supplementary Information for description of building typologies).

The transition

We explore four scenarios for a transition to mass timber in the construction of urban buildings over thirty years: from 2020 until 2050. Thirty years has been suggested as a reasonable timeframe for climate action[23]. It also provides sufficient time for industries to scale up their manufacturing. Over thirty years in the past, cement, steel and aluminium industries grew in their capacity by 370%, 216% and 490%, respectively[50]. We have limited the scope of our analysis to the demand for and construction of anticipated new buildings, their net storage potential of carbon, and carbon emissions associated with transfer of carbon from forests into cities.

The pace of the transition, we propose, is determined by the percentage of new urban buildings designed with timber (see Supplementary Information for details). Four transition scenarios are considered: (1) 'business as usual', in which the majority of new buildings (99.5%) are constructed with steel and concrete and 0.5% with timber; (2) '10% timber', in which countries with the demonstrated capacity to manufacture mass-timber products or countries located close to those with manufacturing capacities primarily use engineered timber for the construction of new urban buildings; (3) '50% timber', in which those countries without current manufacturing capacity, but with a high potential to build mass-timber facilities, construct new urban buildings with timber; and (4) '90% timber', in which countries with current low industrialization levels also make the transition to timber in urban construction through the evolution of the construction and material manufacturing sector.

In addition to the availability of forest resources, this transition will require changes in building codes, retraining the construction workforce, expansion of manufacturing capacities for bio-based products, and downscaling production of mineral-based materials. While some European and North American countries have adjusted their building codes to allow construction of mid-rise and in some cases high-rise buildings out of wood, many others still need to adopt appropriate regulations. A requirement to report embodied energy in new buildings is currently explored as an incentive to choose low-carbon materials in construction in Vancouver, Canada[51]. The transition will lead to downscaling of cement, steel, aggregate, limestone, and iron ore mining and production. A similar radical industrial transition from fossil fuel to renewable energy sources is currently under way, and this experience can be used to move to bio-based material manufacturing. China's coal use, for example, swung from 3.7% growth in 2013 to a decline of 3.7% in 2015[52].

Carbon storage. Our analysis suggests that construction of timber buildings for new urban dwellers could store 0.01–0.68 GtC yr^{-1} depending on the scenario and the average floor area per capita (Supplementary Table 10). Such an approach would increase the existing carbon sink in long-lived wood products, which has fluctuated between 0.05 and 0.09 GtC yr^{-1} (ref. [53]). The carbon storage in mass-timber buildings will offset some of the temporary reductions of carbon stock in forests, which will re-grow and continue to absorb carbon from the atmosphere. This transfer of carbon from forests into cities may compensate for the weakening of the land-based carbon sinks[12,15] as air temperatures rise and the frequency of natural disturbances relating to climate change that affect forests increases.

The fraction of future urban buildings designed with timber and their floor area per capita will determine the rate of carbon transfer from forests and total storage of carbon in those buildings. The total carbon stored over thirty years would sum up to 2–20 Gt in the 90% timber scenario, 1–11 Gt in the 50% timber scenario, and 0.25–2.3

Gt in the 10% timber scenario (Supplementary Table 10). The primary superstructure would account for the largest share of carbon storage (~80%) in a building assembly, while enclosure composed of CLT and cellulose insulation only for ~20% of the total. Carbon accumulated in timber cities over thirty years would amount to 0.1–9% (depending on the scenario) of the current carbon pool in living tree aboveground biomass (~220 GtC[54]). It would increase the existing carbon pool of urban areas (1–12 GtC[55]) by 25 to 170%. In addition to timber, other traditional bio-based materials, for example, bamboo, straw, hemp, and emerging bio-based materials with high carbon content[56] (~90% instead of ~50% for wood) need to be explored. Optimal mixtures of bio-based construction materials will likely depend on the local climate and the natural resources available.

The aboveground carbon density of a city increases with rising housing density and building height if buildings are designed with timber. Carbon density of timber buildings can surpass that of soil and trees in a mid-rise city, although soil and trees store more carbon than buildings in suburban developments[57]. A five-storey residential building structured in laminated timber can store up to 186 kgC m^{-2} in the primary structure[42]; that is more than in the aboveground biomass of the natural forest with the highest carbon density (52 kgC m^{-2}; typical for the Coast Range ecoregion of North America[58]).

Decision-making around the end of a timber building's life is crucial for the success of this transition as a climate mitigation strategy. Carbon stored in timber buildings has to be preserved on land as long as possible. Timber buildings have to be designed with this goal in mind. It can be achieved by not only designing timber buildings so that their components can be reused or recycled, but also by encouraging collection of timber from demolished buildings, and the stimulation of a market for used wood products. Wood recovery is the first and best option. Utilizing the large structural components associated with mass-timber assemblies facilitates their dismantling and direct reuse after a building's demolition. Smaller components can be recycled in secondary structural and non-structural applications such as flake for panel boards, cellulose insulation or interior finish products. Although biomass combustion is often prioritized as a means of energy recovery[59], conversion of smaller components unsuitable for recycling into a biochar-based material with a very high carbon content[56] might be more effective in restoring carbon storage on land.

Carbon emissions. If we continue to build with steel and concrete from 2020 until 2050 and the global floor area per capita averages at 30 m^2 (ref. [60]) (business as usual scenario, Fig. 3), the cumulative emissions from manufacturing materials for new urban buildings will reach 4.4 GtC. If living standards in new urban areas increase so that the floor area per capita approaches the global maximum (79 m^2 per capita[60] in 2000), emissions from manufacturing mineral-based construction materials may reach 19 GtC, that is 20% of the pertinent carbon budget remaining for 2020–2050 (see Supplementary Information for details).

In the 10% timber scenario, the emissions from production of steel and concrete will continue to dominate the total emissions from manufacturing construction materials for new buildings (Fig. 3). If 50% of new urban dwellers are accommodated in timber buildings, the share of emissions from mass-timber production increases to 30% of the total emissions. The cumulative emissions from manufacturing mass-timber materials are lower than those from mineral-based materials not only because of relatively low embodied emissions of mass timber, but also because of the lower material intensity of wood compared to mineral-based materials (Fig. 2). Low material intensity reduces the material stock per floor area or capita, an important contributing factor to the embodied emissions of materials that has implications for the energy demand for materials
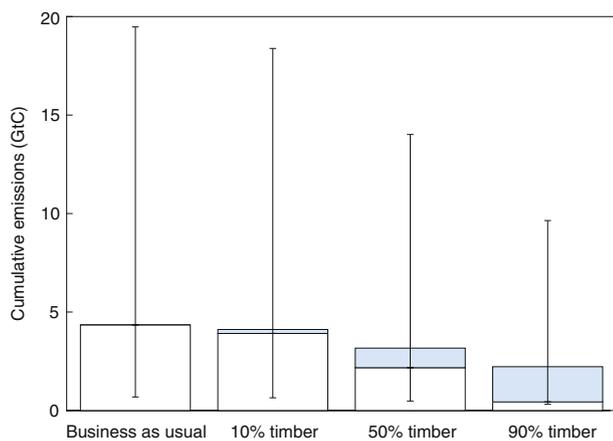
Fig. 3 | Cumulative carbon emissions from manufacturing construction materials needed to construct buildings for new urban dwellers in 2020–2050. Carbon emissions are from manufacturing materials for primary structures and enclosures. Light-blue bars depict emissions from manufacturing mass timber. White bars refer to the emissions from the production of steel and concrete. The error bars indicate uncertainty in the cumulative emissions from manufacturing materials needed for new buildings with maximum and minimum floor area per capita and CO_2 emission coefficients for steel, concrete and timber. These estimates neither account for carbon emissions from forests after timber harvest nor for carbon uptake of re-growing forests. They also do not include the carbon storage potential of wood as a means to offset emissions.

transportation and building construction. The material intensity of concrete is an order of magnitude higher than that of metals and bio-based materials[61]. In our study, a primary structure composed of steel and concrete contains 12.3 t of materials per capita, while one designed with timber is 50% lower (Supplementary Table 3). Because a timber building has lower weight it needs a smaller foundation and fewer construction materials, which are almost always dominated by energy-intensive concrete[43].

The most drastic shift to timber buildings (90% timber scenario) will yield the most savings of carbon emissions. In this case, emissions from mass-timber production exceed the emissions from mineral-based materials and account for 80% of the cumulative emissions from materials manufacturing (light-blue bar in the 90% timber scenario, Fig. 3). The added processing steps and the introduction of chemical adhesives in the lamination process combine to increase the embodied energy of mass timber and associated CO_2 emissions as compared to those of solid wood (logs)[38]. While scaling up the mass-timber industry, CO_2 emissions from mass-timber manufacturing and related forestry operations will ultimately have to be reduced. A recent study demonstrated that these emissions can be disproportionally high in regions with active forestry operations: the net emissions from the forest sector amounted to 50% of emissions from the energy sector including transportation, residential/commercial, industrial and agricultural emissions in Oregon, United States[62]. A reduction can be achieved by improved forest harvest and product manufacturing efficiencies, longer forest rotations, using renewable energy sources, using lignin-based adhesive technologies or mechanical lamination[63] techniques. These latter improvements would avoid the massive increase in the production of synthetic glues and adhesives and their potentially harmful chemical residues in wood waste at the end of a building's life.

The uncertainties in our estimates (Fig. 3) reflect the uncertainties in the future CO_2 emissions per unit of material produced and the floor area per capita of the new urban settlements (Supplementary Tables 3 and 6). Urbanization has very different patterns around the

world; from compact to dispersed, which is reflected in the large variation of floor area per capita and respectively in the large error bars of Fig. 3. It implies that cumulative emissions can increase not only because more people will need housing and other infrastructures in cities and this construction will entail carbon intensive materials, but also because people may live in flats that are more spacious in the future. The estimated uncertainties do not account for the anticipated continuous decline in ore grades and the associated higher energy inputs required to produce mineral-based materials[64] in the future. They also do not include the potential increased use of recycled steel from demolished buildings or landfill mining decreasing CO_2 emissions from steel manufacturing[30].

Transition to bio-based materials will affect not only energy demand and CO_2 emissions of materials manufacturing, but also those of building assembly, maintenance and use, as well as demolition[65,66], which we could not quantify in this study. Data needed for a comprehensive assessment of the use and end-of-life stages of buildings are still scarce in scientific literature[67].

Wood supply in world forests. The demand for forest products entailed in the transition from conventional materials to new wood systems for buildings raises the fundamental question of the potential impacts on the world forests. Increased use of timber in construction will require harvesting 0.02–0.15 GtC yr^{-1} in the 10% timber scenario, 0.08–0.75 GtC yr^{-1} in the 50% timber scenario, or 0.15–1.36 GtC yr^{-1} in the 90% timber scenario over thirty years (Supplementary Table 10, Fig. 4). This demand could potentially be covered by combining harvests from both softwood and hardwood tree species[38,68] as well as from bamboo[69], a giant grass native to tropical and subtropical regions of all continents except Europe.

Timber needed for new buildings will have to be extracted in addition to roundwood already being taken out for other long-lived wood products (0.24–0.47 GtC in 2015[70]). If the use of roundwood currently used for short-term products, for example, fuel wood, is reconsidered and a larger fraction of the roundwood produced globally (additional 10% of 1–1.6 GtC in 2015[70]) becomes available for construction, then the demand for mass-timber construction of the 10% timber and the minimum demand of the 50% timber scenarios could be satisfied even with the current harvest rates. Although some wood used for short-term products may not be useful for manufacturing structural mass-timber products because of its low mechanical properties or straightness, it may still be used for manufacturing cellulose insulation or particle and strand boards used in enclosure. Re-directing roundwood from use as a fuel (50% of the 2015 roundwood harvest[70]) to long-lived products would be the most beneficial for climate change mitigation; its benefits have been demonstrated for Canada[44] and Europe[71]. The fundamental difference in using timber for long-lived products rather than biofuels is the fate of carbon after timber harvest. While all carbon contained in 1 t of timber is emitted to the atmosphere when timber is burned, this carbon will be retained on land if timber is converted to long-lived wood products. In the latter case, carbon has a potential to be stored on land indefinitely once technologies are developed to process and safely landfill unrecyclable wood from demolished buildings.

An analysis of the past timber harvests reveals the potential to extract more timber if re-directing roundwood use appears problematic. Our analysis of the absolute net annual increments, which indicates forest growth, and wood removals or harvest from 1990 to 2010 shows that 43 out of 65 evaluated countries[72] harvested less wood than grown by forests (see Supplementary Information). Overharvesting in countries where wood removals exceeded the net annual increment has declined from 0.09 GtC yr^{-1} in 1990 to 0.05 GtC yr^{-1} in 2010 (Supplementary Table 8, Extended Data Fig. 2). These data imply that 66% of countries analysed had the capacity to harvest more timber in 2010.
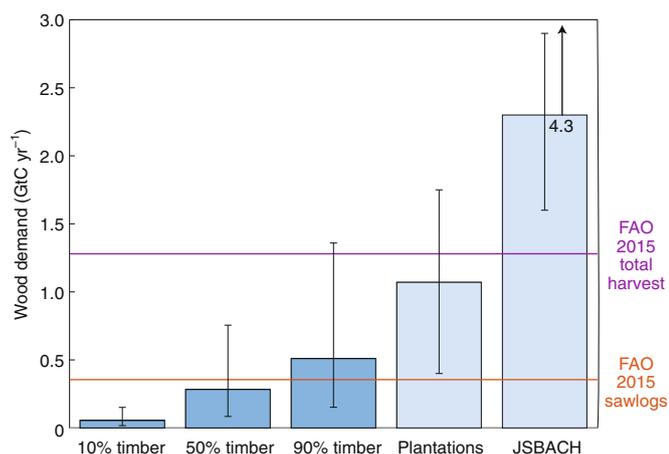
Fig. 4 | Comparison of projected wood demand needed for construction and wood supply available from the world forests. The wood demand (dark-blue bars) and wood supply (light-blue bars) are provided for 2020–2050. Forest harvest projected for forest plantations[73] and by the JSBACH model[74] are used as proxies for wood supply. The horizontal lines indicate roundwood harvested globally in 2015 as documented by FAO[70]. Timber demand is estimated for primary structures and enclosures of new buildings. The upper and lower points of error bars of wood demand represent the total amount of timber required for construction assuming global maximum and minimum floor area per capita[60], respectively. The upper and lower bounds of the error bars for forest harvest represent maximum and minimum estimates of harvested wood under different scenarios described in the Supplementary Information. Wood demand for the business as usual scenario is not shown because it is less than 0.01 GtC yr^{-1}.

Their unexploited harvest potential (0.68 ± 0.26 GtC yr^{-1} in 2010, Supplementary Table 8) could cover the demand of the 10% timber scenario (0.12–0.15 GtC yr^{-1}, Supplementary Table 10) and even the demand of the 50% and 90% timber scenarios (0.28 GtC and 0.51 GtC yr^{-1} respectively, Supplementary Table 10) if the floor area per capita in the newly built timber cities remains at the current global average of 30 m^2.

The estimates of the future forest harvest also suggest that more wood can be harvested without compromising the sustainable regrowth of forest resources over the next thirty years (Fig. 4). To date, planted forests occupy 7% of the world's forest area, but grow 40% of the wood harvested globally[48]. Wood production from those sources is projected to reach 0.4–1.75 GtC in 2050[73], which would fully cover the additional demand for building timber cities for the 10% timber scenario (0.12–0.15 GtC yr^{-1}, Supplementary Table 10). The wood from plantations would also partially cover the demand of 50% and 90% timber scenarios (0.09–0.75 and 0.15–1.36 GtC yr^{-1} respectively). Projections of sustainable forest harvest estimated by the global vegetation model JSBACH[74] for non-protected forest areas showed that sustainable annual wood harvests could increase up to 3.6–4.9 GtC globally by 2050.

In tropical and subtropical regions, where bamboo thrives and demand for building materials in growing cities will be the greatest, bamboo cultivation can curb deforestation and provide steady income to small-scale landowners and low-income rural communities. Bamboo has carbon storage capacity similar to that of non-swidden agroforest, but a substantially higher growth rate than trees[75]: bamboo can be harvested after only seven years, while forests only after decades. While laminated bamboo is definitely a viable alternative to mass timber in structural applications[69] and its use in construction may reduce the pressure on forests, the environmental implications of manufacturing these two construction

materials still have to be carefully compared. Displacement of forests with bamboo should not be an option.

Changes in forest management will likely result in complex biophysical and biochemical feedbacks, which we cannot yet quantify at the global scale. The increase in forest harvest rates will reduce short-term forest carbon stocks and raise CO_2 emissions from harvested forest areas[44,71]. Changes in forest management will also alter surface albedo, land-surface roughness, emissions of volatile organic compounds, transpiration and sensible heat flux, and may lead to subsequent changes of regional climate[10]. Increased forest emissions from harvested areas could be partially offset by reduced deforestation from mineral and metal mining[35] and by carbon sequestration of undisturbed aquatic ecosystems if sand mining declines[34]. Carbon sequestration of forests recovering after harvest can also partially counterbalance emissions unless carbon-rich primary forests are harvested, because young and re-growing forests have an accelerated photosynthetic carbon uptake[76]. Like other managed environmental systems[77], sustainable forest management can lead to a new steady state of forest carbon stocks and an establishment of a constructed carbon pool of timber cities (Fig. 1, right panel). This will follow the transition period with increased CO_2 emissions, which are the costs of enhancing the urban carbon pool and will be balanced by carbon uptake of re-growing forests over time.

Conclusions

In comparison to other engineered carbon sinks, the option of storing carbon in buildings has obvious benefits. It takes advantage of evolving construction processes that will occur in any case, and serves as a substitute for mineral-based structural materials causing high CO_2 emissions. Mass timber is a safer way to store carbon than pumping CO_2 underground[78] and is a more useful and economically viable option than burying logs in trenches under a thick layer of soil[79] for long-term storage or direct conversion of roundwood into biochar. Most notably, the carbon pools in timber cities have to be maintained and gradually enhanced along with forest carbon pools to ensure long-term lock-in of carbon on land, which can be achieved through more durable construction detailing that promotes a longer timber building life span, stimulating markets for used wood and for technologies that convert used wood into other long-living products along with the sustainable management of forests.

A precondition for achieving higher harvest levels and maintaining carbon storage in forests is preserving forest sustainability and continuing re-forestation efforts. Increased demand for timber in construction would have to be supported by a strong legal and political commitment to sustainable forest management, robust forest certification schemes, empowerment of people living in forests, efforts to curb illegal logging and exploring bamboo and other plant fibres as a replacement for timber in tropical and subtropical regions. Biologically valuable or vulnerable forests must be left in reserve[48]. The increased demand for engineered wood products could help finance and ensure Sustainable Forest Management[80] (for example, Farmer Managed Natural Regeneration[81]) and thus contribute to avoiding deforestation driven by agricultural expansion, mining, and to securing a multitude of other functions and services provided by forests. A transition to timber cities would have to proceed in parallel with active reforestation and forest restoration efforts.

The use of timber or bamboo could keep or revive cultural-specific methods of construction and thereby preserve cultural heritage in many regions of the world[82]. In the twenty-first century wood is still utilized by ~1 billion people in Asia and Oceania and ~150 million people in Africa, where forest products are the main materials used for walls, roofs or floors[83].

The history of transcultural familiarity with wood- and plant-based construction material and assemblies, especially in Asia,

Oceania and Africa[82,83], suggests an alternative future for buildings. In a few decades, a material revolution, scaled in its application to global urbanization and to the sustainable capacities of its forest sources, may balance material supply, material demand and environmental burdens and benefits, while answering the challenge of urgent climate action. We recommend from this perspective a new set of building design and planning policy criteria that emphasize the development and implementation of low fossil carbon strategies, centred upon the incorporation of new and sophisticated forms of bio-based products and building systems into the formation of future human settlements.

Data availability

All data analysed in this study are included in its supplementary information files.

Code availability

The mathematical algorithm used in this study is available from the corresponding author upon reasonable request.

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Author contributions

G.C., A.O. and H.J.S. designed the study. A.O. and A.R. provided building typologies and associated data. C.P.O.R. and G.C. assessed the timber amounts available from the world's forests. G.C. developed methods for estimating carbon emissions and storage at the global scale. B.K.R. and T.E.G. provided expertise for steel materials and embodied energy calculations. Z.L. provided expertise for cement and concrete and respective data. K.V. supplied expertise on political, social and cultural implications of the transition. All authors contributed to discussing the results and writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Supplementary information is available for this paper at https://doi.org/10.1038/s41893-019-0462-4.

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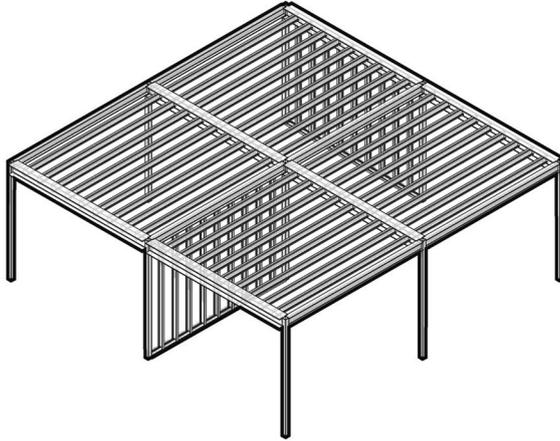**Reprints and permissions information** is available at www.nature.com/reprints.

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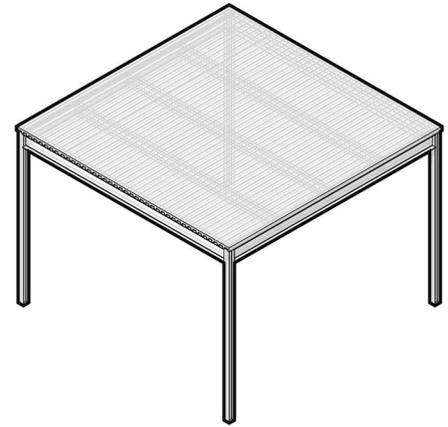
RESIDENTIAL

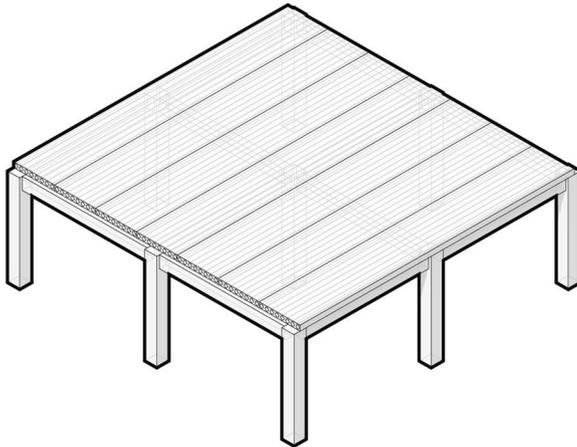**COMMERCIAL**

SYSTEM I
STEEL

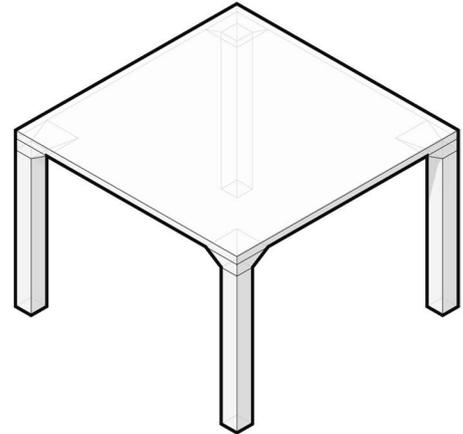Structural steel frame with lightweight steel shear walls

Structural steel moment frame with composite corrugated steel and concrete floor deck
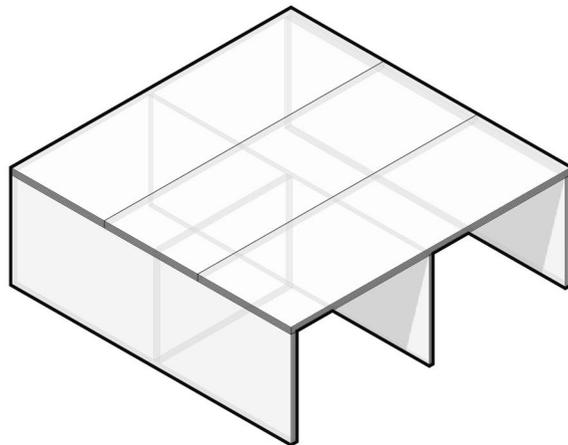
SYSTEM II
CONCRETE

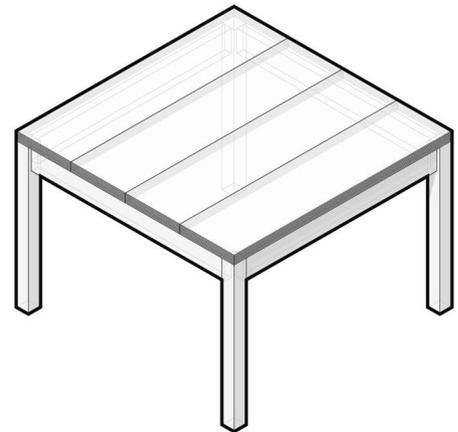Precast concrete post and beam components with a precast holllow core concrete slab

In-situ site-cast concrete columns supporting a reinforced flat-plate concrete floor
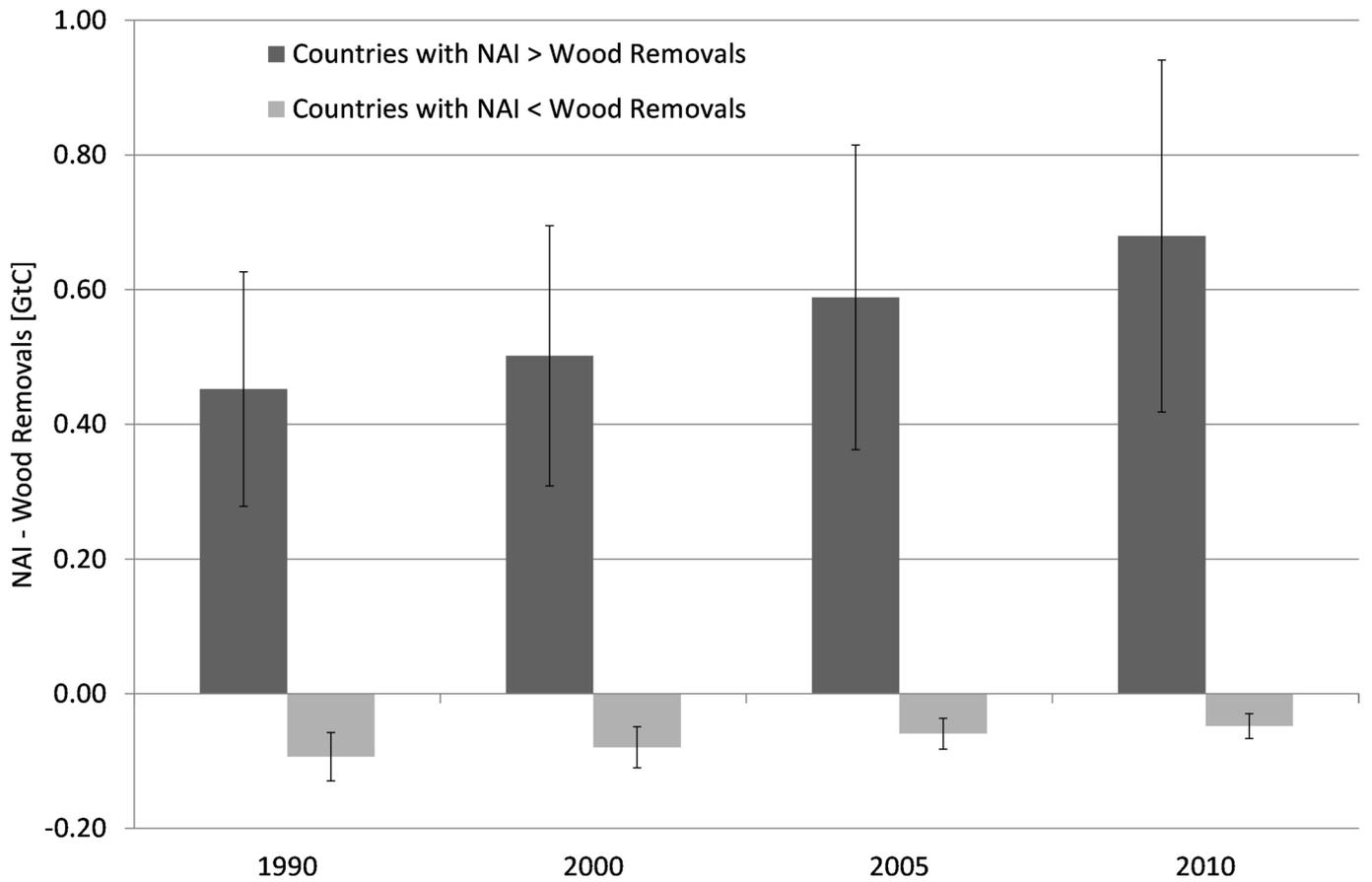
SYSTEM III
TIMBER

Cross-laminated timber bearing walls and floor panels

Glue-laminated columns and beams with cross-laminated timber floor panels

Extended Data Fig. 1 | Primary structures designed for typical, mid-rise residential and commercial building morphologies.

Extended Data Fig. 2 | Difference between absolute net annual increment (NAI) and wood removals for the non-protected forest area of sixty-five FAO countries/regions for 1990–2010. The bars indicate how much newly grown wood (NAI) is available after subtracting wood removals for sixty-five countries/regions grouped by the sign of this difference. Black bars indicate that the increment is larger than the wood removals. Grey bars indicate that the removals are larger than the increment. Error bars indicate the range induced by using a minimum and maximum wood density of 400 and 900 kg m^{-3} respectively when calculating the carbon content.