Barriers and opportunities of fast-growing biobased material use in buildings

BUILDINGS & CITIES

SYNTHESIS PAPER

ubiquity press

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ABSTRACT

Limiting global warming to 1.5°C requires immediate and drastic reductions in greenhouse gas (GHG) emissions. A significant contributor to anthropogenic global GHG emissions is the production of building materials. Biobased materials offer the potential to reduce such emissions and could be deployed in the short term. Timber construction has received the main attention from policy and industry. However, the implementation of timber construction at the global scale is constrained by the availability of sustainably managed forest supplies. A viable alternative is fast-growing plants and the use of agricultural waste products. These can be deployed faster and are better aligned to local supplies of biomass and demands from the building sector. Fast-growing materials are generally able to achieve net-cooling impacts much faster due to their short rotation periods. The GHG emissions due to the production of biogenic building material can be compensated by regrowth of the new (replacement) plant and, overall, this will absorb CO_2 from the atmosphere. A range of biogenic materials can be promoted and used as insulation materials and structural materials.

POLICY RELEVANCE

Materials play an important part of the transition to a low carbon society, especially as many existing construction materials have large amounts of 'embodied carbon' in their manufacture. Given the need to rapidly reduce GHG emissions, public policies can promote a rapid transition to low carbon biogenic materials. The use of fast-growing biogenic materials for use in construction products can create carbon-neutral or even carbon-negative products. The use of biogenic materials in construction materials delivers larger GHG savings than their use in other sectors (*e.g.* biofuels). The use of these materials can be scaled up quickly due to their short rotation period. An integrated policy approach is needed that provides synergy between the energy, industry, housing and agriculture sectors to encourage the use of biobased materials.

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KEYWORDS:

biobased; biogenic; buildings; carbon sink; construction materials; low carbon society; transition

TO CITE THIS ARTICLE:

Göswein, V., Arehart, J., Phan-huy, C., Pomponi, F., & Habert, G. (2022). Barriers and opportunities of fast-growing biobased material use in buildings. *Buildings and Cities*, 3(1), pp. 745–755. DOI: https://doi.org/10.5334/bc.254

DOI: 10.5334/bc.254

1. INTRODUCTION

Climate change is no longer just a future scenario but a present reality. Recent years saw an increased pace of 'natural' disasters around the world. Raging bushfires in Australia in 2019 and 2020 cost A$100 billion (Read & Denniss 2020) and harmed 3 billion animals (Vernick 2020). Heavy rainfalls leading to floods in Germany in 2021 destroyed entire villages and killed more than 180 people (BPB 2021). Droughts and changing weather led to failed harvests causing hunger and loss of income, which has forced mass emigration from Guatemala during the last few years (Steffens 2018). And these are just a few examples.

Climate change is primarily a threat to our livelihood and that of our planet, and by extension also to our economic wellbeing and political stability. For this reason, many countries have agreed to reduce greenhouse gas (GHG) emissions. Around 40% of anthropogenic GHG emissions are linked with building activities (UNEP 2022). Half of those emissions are associated with embodied carbon in materials and the construction process. The other half of built environment GHG emissions is attributed to the operation of buildings. There has been significant progress to improve energy performance and efficiency of building operation, but not for the embodied carbon in materials (Röck *et al.* 2020).

Society is putting its hope on high-tech solutions to solve the climate crisis (Allwood 2018). In Europe and the US, three-dimensional (3D) printing for optimised structures, robotic construction or the use of artificial intelligence for optimised deconstruction are often considered as solutions for current construction challenges (Adaloudis & Bonnin Roca 2021; De Schutter *et al.* 2018). However, most of these technologies are not feasible for large-scale implementation since the necessary tools, equipment and know-how come at high costs (Allwood 2018). Another attractive technology is carbon capture and storage (CCS) for cement and steel production. This technology, although promising and useful in the long run, will be difficult to implement widely in the very short term. The Carbon Capture and Storage Institute stated that installation capacities have been reduced by 30% between 2010 and 2020, while they need to scale up by 14,000% over the next 20 years (Page *et al.* 2020).

Two questions arise:

- Given the urgency of the climate crisis, what are economically (and environmentally) viable solutions for building materials?
- What actions are needed to support this transition?

2. MATCHING SUPPLY AND DEMAND

2.1 GLOBAL NORTH

A widely promoted solution to tackle embodied emissions of materials, advocated by researchers and policymakers, is for timber to replace concrete and steel in construction (Churkina *et al.* 2020; Mishra *et al.* 2022). Yet, a building constructed from timber alone just transfers carbon from one carbon pool (the forest) to another carbon pool (the built environment) (Arehart *et al.* 2021). Timber construction typically releases significantly less GHGs into the atmosphere compared with mineral-based construction, *e.g.* steel, concrete, *etc.* (Heeren *et al.* 2015). But this is also contingent on whole life-cycle considerations. However, the climate benefit associated with biogenic carbon storage is only achieved when another tree grows, which takes decades. Within a short time horizon (*i.e.* until 2050) timber construction is not climate neutral (Hawkins *et al.* 2021) and sufficient resources are not readily available to meet demand.

Pine trees, a common source for structural material, take 25–30 years to reach maturity. A letter addressed to the European Commission and administrations of the US, Japan and South Korea, signed by more than 500 renowned scientists, called for caution: forest regrowth requires time, which currently is not available (Raven *et al.* 2021). In fact, the expanding bioeconomy already forces an increased demand on wood harvest, which is likely to hamper the global vision and targets for forest-based climate mitigation (Ceccherini *et al.* 2020). Pressure on forest will be further increased due to rising temperatures and increased water stress (Bauman *et al.* 2022).

The slow population growth and existing high rate of urbanisation (UNDESA 2018) mean that current construction rates of new buildings in the Global North are generally low. Instead, the main material demand is for stricter energy efficiency measures and refurbishment of existing buildings (Heeren & Hellweg 2019).

The emphasis on retrofitting the existing building stock in the Global North presents an opportunity to use straw (an agricultural waste product) as a biobased thermal insulation material. To assess the feasibility of using straw in the Global North, a simple model is constructed to evaluate the future demand and future supply. To model the demand, a 3% retrofit rate in the Global North is assumed, based upon what has been conceptualised by regulatory agencies as what is needed to achieve climate neutrality (BPIE 2021).

To model the supply side, straw availability is calculated using Food and Agriculture Organization (FAO) statistics for 'wheat area harvested' (FAO 2019) at the country level. The wheat area harvested is converted into straw, using an average wheat-to-straw ratio of 6.5 tons/ha, considering soft red winter wheat and soft white spring wheat, as presented by Dai *et al.* (2016). From the resulting straw, straw that must be left behind to conserve soil quality (sustainable straw extraction) and conventional competitive uses (*i.e.* feed, bedding, fibre uses, *etc.*) was subtracted, together accounting for 32%, as estimated by the Netherlands Programmes Sustainable Biomass (Lesschen *et al.* 2013). The resulting demand and supply balance for straw is visualised in ***Figure 1***.

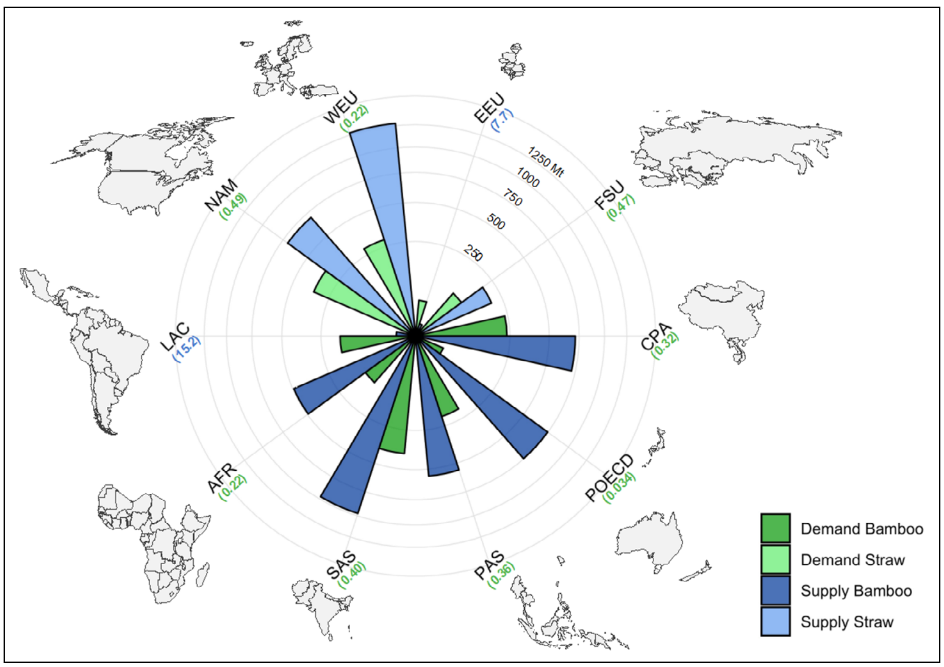

Figure 1: Balance of the available supply of biomass and potential demand for biomass (Mt) between 2021 and 2050.

Note: Results are shown for straw—in the Eastern European Union (EEU), Former Soviet Union (FSU), North America (NAM), and Western European Union (WEU)—and for bamboo—in Latin America (LAC), Africa (AFR), South Asia (SAS), Pacific Asia (PAS), Pacific member of the Organisation for Economic Co-operation and Development (POECD) and Centrally Planned Asia and China (CPA)—across geo-clusters. The ratio between demand and supply is noted for each region, with values < 1.0 indicating a sufficient supply in the region, while numbers > 1.0 indicate an insufficient supply in the region. In most regions there is sufficient supply to meet demand, and the overall global demand-to-supply ratio is 0.30. Thus, policy that incentivises the use of biobased materials in new construction and retrofits is feasible globally from a demand-and-supply balance.

It is difficult to estimate the competing uses of straw as a large portion will stay on the farm to supply animal bedding. Some studies consider that 60–70% of straw production could be currently used for other competing activities (mainly soil incorporation and animal bedding) (Scarlat *et al.* 2010; Iqbal *et al.* 2016; Einarsson & Persson 2017). Even though this would reduce the straw availability shown in ***Figure 1*** by a factor of 2, it would still be highly sufficient in North America and Europe. Furthermore, the straw used as feedstock for bioenergy is still marginal. However, because the European Union (EU) is encouraging the use of agricultural residues instead of cultivating dedicated energy crops, the demand from the energy sector is likely to increase (Einarsson & Persson 2017).

2.2 GLOBAL SOUTH

In South America, Africa, China and Southeast Asia, urbanisation and population growth are driving high rates of new construction that require substantial quantities of structural materials. An increased use of wood for structural applications may be inadvisable since the world's rainforests located in these regions are already dwindling (Boulton *et al.* 2022).

Glue-laminated (glulam) bamboo materials for structural systems is a viable technology. To assess the future demand for bamboo, future floor space estimates are derived from Güneralp *et al.* (2017), considering the S50 (medium urban population density) scenario, linearly interpolating between 2021 and 2050. Total material demand is then calculated using the average values for residential glulam bamboo construction (Zea Escamilla *et al.* 2018). The supply of bamboo is assessed using data of bamboo areas (ha) from Xu *et al.* (2019) for China and from the FAO (2007) for other world regions, and coefficients from Zea Escamilla *et al.* (2016) to convert into the available bamboo biomass (metric tonnes). Similar for the Global North, the supply and demand balance of bamboo in the Global South is shown in ***Figure 1***.

The availability of bamboo as a construction material must contend with competing uses. Bamboo forests have multiple uses. In China, for instance, around 30% of forests are primarily used for production (FAO 2021), and within this production, engineered bamboo products, such as glulam bamboo, represent a small fraction (GVR 2019). This means that a more conservative approach of bamboo supply would divide the bamboo supply shown in ***Figure 1*** by a factor of 10, which would lead to the ability to supply half of the housing demand globally. In addition, there is a Chinese ambition to increase bamboo forest size (King 2020), as well as to increase revenue from engineered bamboo (GVR 2019).

The resulting differences between demand and supply show a large over-supply of biobased materials compared with building material demand (***Figure 1***). This is a simplified model, but supply is one order of magnitude larger than what is needed to meet the global demand of bamboo once sustainable management practices are considered. This result challenges a previous analysis on the supply and demand balance of timber construction that found that regions with high construction activities may be unable to supply sufficient wood (Pomponi *et al.* 2020). This finding clearly shows the potential of using fast-growing biobased materials for construction, especially as two of the large variety of fast-growing bio-resources have been explored.

3. ACHIEVING FAST CARBON REDUCTION

The difference for the climate between using fast-growing plants and wood is illustrated in ***Figure 2***. It shows the performance of 1 kg of each material with respect to global temperature change (GTP) as calculated by the methodology of Cooper *et al.* (2020). In such calculations the temporal effect of the GHGs is measured, which considers the direct effect due to carbon sequestration during plant growth as well as carbon emission during building material production. The biomass regrowth model considers a normal regrowth curve (Cherubini *et al.* 2011) with all carbon removed starting at the year of construction and depending on the growth rate of the plant, which takes 90 years for sawn wood (Eriksson *et al.* 2007), 40 years for glulam (Diaz *et al.* 2018), five years for bamboo (Greco 2010) and one year for straw. The life-cycle inventory data are cradle to gate and are from the Ecoinvent database, assuming 'rest-of-world' values, except for glulam (Puettmann & Wilson 2006) and bamboo (van der Lugt & Vogtländer 2015) as data were unavailable in Ecoinvent. Finally, only CO_2 and methane (CH_4) are considered as GHGs, with others assumed to be negligible.

The results show clearly that fast-growing materials achieve net-cooling impacts much faster due to their short crop rotation periods. This result illustrates how the carbon emission due to the production of building material is directly compensated by regrowth of the new plant and, overall, there is a cooling effect on the atmosphere. In contrast, materials that have longer rotation periods contribute in the short term to a warming of the atmosphere, and only achieve a cooling effect decades after implementation into a building. In that sense, the use of wood in construction is contributing to carbon removal from the atmosphere but a cooling effect on the climate is perceptible only decades after construction. In addition, the use of biobased construction products also avoids emissions by the replacement of a more polluting building material.

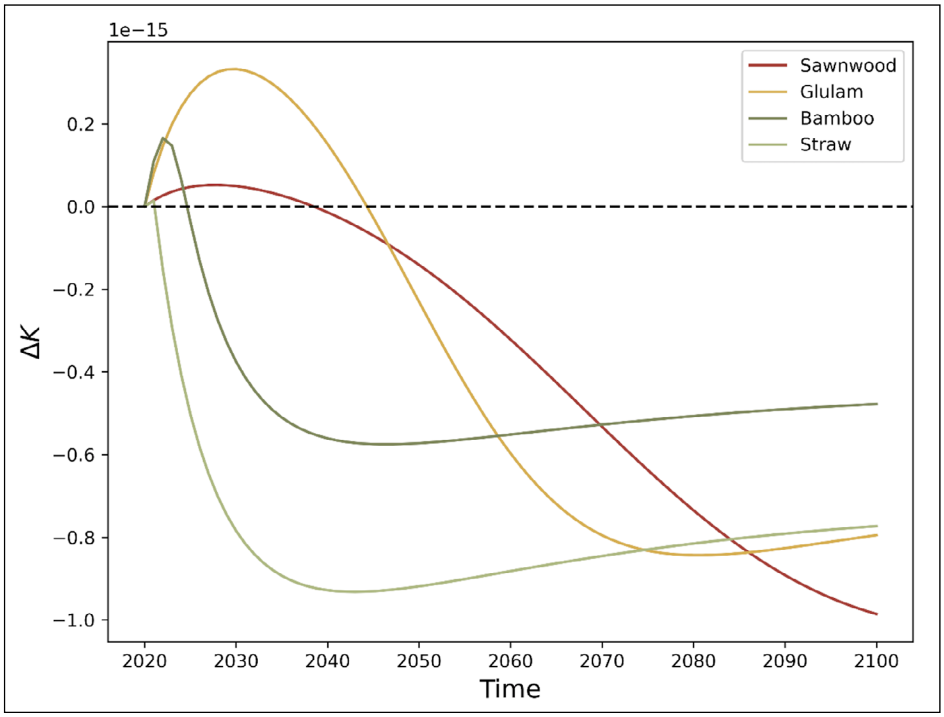

Figure 2: Global temperature change (GTP) of different biobased construction materials considering the production (cradle-to-gate) emission and subsequent biogenic carbon sequestration from replanting of 1 kg of each.

Note: Straw and bamboo allow for fast cooling of the atmosphere in the near term (cooling within a decade) due to short rotation periods, while sawn wood and glue-laminated (glulam) timber only reach negative temperature change starting from about 2040 onwards.

The overall climate benefit of substituting fossil-fuel based materials with biobased products has been quantified through a displacement factor (DF), which expresses the amount of reduced GHG emissions per mass unit of biobased use, when producing a functionally equivalent product (Sathre & O'Connor 2010). Such DF values are sensitive to harvesting rate and the lifetime of the biobased product in the technosphere (Seppälä *et al.* 2019). Wood product values range usually between 0.5 and 2 tC removed per tC in the wood product, but an increase of harvesting in forestry is certainly linked with an increase in GHG emission in the first 30 years (Soimakallio *et al.* 2021) before perceiving benefits. For strawbale, no DF has been calculated so far, but a simple calculation looking at the DF of a strawbale replacing extruded polystyrene (XPS) insulation would lead to similar values, around 0.9 tC/tC, considering the density difference (30 versus 210 kg/m^3 for XPS and strawbale, respectively), the thermal performance difference (0.04 versus 0.06 W/K.m) and their GHG emissions (14.4 versus 0.1 kg CO_2/kg) and storage (0 versus 1.35 kg CO_2/kg) given from the Swiss database KBOB.[1] Such a DF would, however, be achieved in year 1 after construction and, therefore, provide immediate cooling.

The double effect of carbon mitigation and carbon removal can be significant depending on the application and its market share penetration. For example, in Europe, estimations show that if straw is used as insulation material to insulate all existing facades, up to 3% of the total GHG annually emitted by all sectors in 2015 could be removed every year (Pittau *et al.* 2019). Using fast-growing biomass can provide a savings of 6% of current anthropogenic GHG emissions (Arehart *et al.* 2021). This carbon removal needs to be added to the carbon mitigation achieved through improved energy efficiency of buildings as well as carbon avoided through avoided use of fossil-based insulation (*e.g.* stone wool, expanded polystyrene—EPS) which can represent up to 20% of GHG emissions related to the construction sector in certain European countries, such as Switzerland (Heeren & Hellweg 2019).

4. DIVERSITY IS KEY

Moving away from concrete and steel to biobased materials should not just mean a switch from one material to another. This is an opportunity to promote a diverse range of construction materials that respect the diversity of building needs and supply chains. Fast-growing biomass can be used for both structural and thermal insulating purposes. Appropriate biobased material choices consider the local supply chain and availability, sustainable cultivation, climate responsive

DOI: 10.5334/bc.254

architecture, and possibly add value to local agricultural practices by creating new streams for by-products' valorisation, as well as creating jobs in local communities. Today, there are already some promising examples: wheat straw can be turned into an added-value product as insulation material (Pittau *et al.* 2018); bamboo forests can be used to supply building materials in local production workshop allowing farmers to obtain additional revenue from both carbon credits and transformed bamboo products (Zea Escamilla *et al.* 2016). Furthermore, the use of fast-growing biomass provides additional revenues in the hinterlands, which are usually impoverished places.

Diversity of biomass use is also key to minimise the risks of land-use changes and inter-sectoral competition. Here, policymakers can learn from past mistakes made with first-generation biofuel production from maize, sugar cane or vegetable oil. The use of these commodities for biofuel rather than food production can threaten global food security. Moreover, converting forests into farmland is generally not recommended as forests provide an array of ecosystem services (Creutzig *et al.* 2021). To avoid those mistakes, cross-sectoral policies should be developed considering the needs and challenges of the energy, agriculture and building sectors, as well as environmental consequences of land use and land-use change, instead of waiting for market self-regulation (Lapola *et al.* 2014).

5. POLICY LEVERS AND BEYOND

To facilitate the use of biogenic materials for construction, a policy and legal framework is needed.

A legal framework would reassure investors and insurance companies. Devising a legal framework would, of course, need to be tailored to each country's existing legal landscape. The International Standard Organisation (ISO) has recently released standards on bamboo construction for bamboo culm and engineered bamboo (ISO 2021, 2022). This first step allows engineers to design bamboo structures. Similar frameworks are needed for the use of agricultural waste products (*e.g.* straw) in construction materials.

A robust supply chain of materials is needed. The current policies for afforestation linked with carbon storage strategies can have synergetic effects when bamboo forests are planted. Indeed, bamboo forests reach maturity after five years, after which the first bamboo pole can be extracted, and as no clear cuts are made, the bamboo harvesting maintains the carbon stock of the land (Zea Escamilla *et al.* 2016). China is planning to plant 1 million ha of bamboo by 2030, which will increase the current bamboo forest area by 20% (King 2020).

Changes are needed in the regulatory frameworks to provide clarity and agreement on how to account for the potential benefit of temporary carbon storage in biogenic materials (Hoxha *et al.* 2020). For instance, neither Switzerland nor Germany includes temporary carbon storage in carbon accounting, which gives only the substitution advantage to biobased materials. In contrast, France and the Netherlands include negative carbon from biomass, but do not consider the regrowth time, which gives the full DF benefit for the use of biobased materials without accounting for the short-term increase of emissions associated with timber-based products.

Second, alignment with energy policies is needed. In Europe, the primary source of renewable energy is bioenergy (comprising 60% of renewable energy), for which most feedstock is provided by forestry (75% of biomass comes from forestry residues and 25% from agriculture residues) (Scarlat *et al.* 2019). Today, mainly dedicated energy crops are used as feedstock to produce transport biofuel. In the EU, maize is the primary feedstock for ethanol, followed by sugar beet, wheat, other cereals and molasses and, lastly, wastes and residues (European Commission 2020). However, as the subsidies shift from dedicated energy crops to residues (Einarsson & Persson 2017), straw will become a more critical feedstock because the biological composition of straw (a high lignin content) makes it 'highly suitable' for bioethanol production (Iqbal *et al.* 2016). The potential for straw and other agricultural residues as a feedstock for bioenergy (within Europe) has been subject to numerous studies in the past years (Einarsson & Persson 2017; Scarlat *et al.* 2010). In 2019, straw accounted for 75% of the agricultural residues produced in the EU-28 (Scarlat *et al.* 2019). This shift in straw use does not seem beneficial for the climate since bioethanol is only providing a carbon-neutral solution while strawbale insulation is providing a temporary carbon-negative solution.

DOI: 10.5334/bc.254

Third, current EU agriculture policy subsidises straw incorporation in soil to increase soil organic carbon (SOC). Studies reviewed by Powlson *et al*. (2008) have estimated that increasing the SOC of arable land with manure, cereal straw or biosolids (sewage sludge) could compensate 1–2% of annual anthropogenic emissions. However, the increase of SOC per ton of straw incorporated declines significantly after the first 20 years of straw incorporation (Powlson *et al.* 2008). Furthermore, Cook *et al*. (2013) found that the increase of SOC is more significant for applying manure (by a factor of 4) and biosolids (by a factor of 100) than by incorporating straw.

6. CONCLUSIONS

The coordination of an interdepartmental policy strategy between the energy, agriculture, housing and construction sectors can hasten a transition to a low carbon society, in this case by promoting the use of fast-growing biobased materials for construction. Current incentives for farmers to incorporate straw leads to short-term carbon storage, which is not efficient. Current energy incentives might shift part of the straw towards bioenergy production, which leads to zero carbon emission and a very small fraction of energy covered. In contrast, promoting a carbon-negative buildings standard could accelerate the use of strawbale insulation which would allow for a reduction in energy demand in addition to the long-term storage of carbon in the built environment. The policy lever available appears to lie with incentivising changes to the agriculture sector.

To mainstream the use of fast-growing biobased building materials, it is important to act on the many different levels of the value chain, linking resource producers to the final building contractor (Simpson *et al.* 2020). Incentives are needed to motivate farmers to restructure their activities and orient their by-products towards the construction industry. Furthermore, educational institutions need to train construction workers, engineers and architects to work with such materials. Finally, top-down constraints are also required. Laws and local regulations can specify the minimum amount of fast-growing biobased materials in building projects to secure the demand and allow local producers to step up on the supply side. Similarly, public institutions as clients can also use their procurement policies to create demand for fast-growing biobased products in buildings and infrastructure.

In regions where structural material is needed, bamboo forests can supply a significant part of the demand and could supply more with increased bamboo forestry activities and afforestation. In regions where insulation materials are needed, straw is an abundant by-product of wheat production and can already supply the demand in Europe (Göswein *et al.* 2021) and North America. Therefore, timber should not be the primary material of focus in order to turn the global building stock into a carbon sink.

The materials are there in abundance. The technology is ready, tested and already implemented in a multitude of buildings. What is lacking is a structured value chain. Positive change can be created quickly by creating both supply push (agriculture incentive) and demand pull (public procurement and regulatory demand). Middle actors will need training provided by established construction associations or the vocational and professional education sector. Shifting future buildings to use a wide range of fast-growing biobased materials is a truly sustainable choice, providing climate, financial and social benefit across the globe.

NOTE

1 See https://www.kbob.admin.ch/kbob/de/home.html/.

ACKNOWLEDGEMENTS

The authors acknowledge the valuable inputs from three anonymous reviewers and the editor-in-chief, which considerably strengthened the manuscript.

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GH: writing, conceptualisation, interpretation of the results, reviewing; FP: writing, conceptualisation, methodology, interpretation of the results, reviewing; VG: writing, data collection, data analysis, interpretation of the results, reviewing; JA: writing, data collection, data analysis, visualisation, interpretation of the results, reviewing; CPH: data collection, data analysis, reviewing.

COMPETING INTERESTS

The authors have no competing interests to declare.

REFERENCES

Adaloudis, M., & **Bonnin Roca, J.** (2021). Sustainability tradeoffs in the adoption of 3D concrete printing in the construction industry. *Journal of Cleaner Production*, 307, 127201. DOI: https://doi.org/10.1016/j.jclepro.2021.127201

Allwood, J. M. (2018). Unrealistic techno-optimism is holding back progress on resource efficiency. *Nature Materials*, 17, 1050–1051. DOI: https://doi.org/10.1038/s41563-018-0229-8

Arehart, J. H., Hart, J., Pomponi, F., & **D'Amico, B.** (2021). Carbon sequestration and storage in the built environment. *Sustainable Production and Consumption*, 27, 1047–1063. DOI: https://doi.org/10.1016/j.spc.2021.02.028

Bauman, D., Fortunel, C., Delhaye, G., Malhi, Y., Cernusak, L. A., Bentley, L. P., Rifai, S. W., Aguirre-Gutiérrez, J., Menor, I. O., Phillips, O. L., McNellis, B. E., Bradford, M., Laurance, S. G. W., Hutchinson, M. F., Dempsey, R., Santos-Andrade, P. E., Ninantay-Rivera, H. R., Chambi Paucar, J. R., & **McMahon, S. M.** (2022). Tropical tree mortality has increased with rising atmospheric water stress. *Nature*, 608, 528–533. DOI: https://doi.org/10.1038/s41586-022-04737-7

Boulton, C. A., Lenton, T. M., & **Boers, N.** (2022). Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nature Climate Change*, 12, 271–278. DOI: https://doi.org/10.1038/s41558-022-01287-8

BPB. (2021). *2021 Century floods in Germany* [in German]. Bundeszentrale für Politische Bildung (BPB). https://www.bpb.de/kurz-knapp/hintergrund-aktuell/337277/jahrhunderthochwasser-2021-in-deutschland/

BPIE. (2021). *The make-or-break decade: Making the EPBD fit for 2030* (Policy Brief). Buildings Performance Institute Europe (BPIE).

Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., & **Cescatti, A.** (2020). Abrupt increase in harvested forest area over Europe after 2015. *Nature*, 583, 72–77. DOI: https://doi.org/10.1038/s41586-020-2438-y

Cherubini, F., Peters, G., Berntsen, T., Strømman, A., & **Hertwich, E.** (2011). CO_2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. *GCB—Bioenergy*, 3, 413–426. DOI: https://doi.org/10.1111/j.1757-1707.2011.01102.x

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & **Schellnhuber, H. J.** (2020). Buildings as a global carbon sink. *Nature Sustainability*, 3, 269–276. DOI: https://doi.org/10.1038/s41893-019-0462-4

Cook, S., Nicholson, F. A., Kindred, D. R., & **Bhogal, A.** (2013). *Straw incorporation review* (Research Review No. 81, July). ResearchGate. DOI: https://doi.org/10.13140/RG.2.1.2364.2721

Cooper, S. J. G., Green, R., Hattam, L., Röder, M., Welfle, A., & **McManus, M.** (2020). Exploring temporal aspects of climate-change effects due to bioenergy. *Biomass Bioenergy*, 142, 105778. DOI: https://doi.org/10.1016/j.biombioe.2020.105778

Creutzig, F., Erb, K.-H., Haberl, H., Hof, C., Hunsberger, C., & **Roe, S.** (2021). Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *GCB—Bioenergy*, 13, 510–515. DOI: https://doi.org/10.1111/gcbb.12798

Dai, J., Bean, B., Brown, B., Bruening, W., Edwards, J., Flowers, M., Karow, R., Lee, C., Morgan, G., Ottman, M., Ransom, J., & **Wiersma, J.** (2016). Harvest index and straw yield of five classes of wheat. *Biomass Bioenergy*, 85, 223–227. DOI: https://doi.org/10.1016/j.biombioe.2015.12.023

De Schutter, G., Lesage, K., Mechtcherine, V., Nerella, V. N., Habert, G., & **Agusti-Juan, I.** (2018). Vision of 3D printing with concrete—Technical, economic and environmental potentials. *Cement and Concrete Research*, 112, 25–36. DOI: https://doi.org/10.1016/j.cemconres.2018.06.001

Diaz, D., Loreno, S., Ettl, G., & **Davies, B.** (2018). Tradeoffs in timber, carbon, and cash flow under alternative management systems for Douglas-fir in the Pacific Northwest. *Forests*, 9, 447. DOI: https://doi.org/10.3390/f9080447

Einarsson, R., & **Persson, U. M.** (2017). Analyzing key constraints to biogas production from crop residues and manure in the EU—A spatially explicit model. *PLoS ONE*. DOI: https://doi.org/10.1371/journal.pone.0171001

Eriksson, E., Gillespie, A. R., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R., & **Stendahl, J.** (2007). Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forestry Research*, 37, 671–681. DOI: https://doi.org/10.1139/X06-257

European Commission. (2020). *EU agricultural outlook for markets, income and environment, 2020–2030*. Publications Office of the European Union. DOI: https://doi.org/10.2762/252413

FAO. (2007). *World bamboo resources. A thematic study prepared in the framework of the Global Forest Resources Assessment*. Food and Agriculture Organization (FAO) of the United Nations. https://www.fao.org/3/a1243e/a1243e00.htm

FAO. (2019). *Data for crops—Wheat area harvested*. Food and Agriculture Organization (FAO) of the United Nations.

FAO. (2021). *Global Forest Resources Assessment: National data for China—Management objective*. Food and Agriculture Organization (FAO) of the United Nations.

Göswein, V., Reichmann, J., Habert, G., & **Pittau, F.** (2021). Land availability in Europe for a radical shift toward bio-based construction. *Sustainable Cities and Society*, 70, 102929. DOI: https://doi.org/10.1016/j.scs.2021.102929

Greco, T. M. (2010). *Bambu: cultivo e manejo*. Insular.

Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P. L., Fragkias, M., Li, X., & **Seto, K. C.** (2017). Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, 114, 8945–8950. DOI: https://doi.org/10.1073/pnas.1606035114

GVR. (2019). *Bamboos market size, share & trends analysis report by application (industrial products, shoots, furniture, raw materials), by region (North America, Europe, APAC, CSA, MEA), and segment forecasts, 2021–2028* (Report No. GVR-2-68038-819-0). Grand View Research (GVR). https://www.grandviewresearch.com/industry-analysis/bamboos-market

Hawkins, W., Cooper, S., Allen, S., Roynon, J., & **Ibell, T.** (2021). Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. *Structures*, 33, 90–98. DOI: https://doi.org/10.1016/j.istruc.2020.12.013

Heeren, N., & **Hellweg, S.** (2019). Tracking construction material over space and time: Prospective and geo-referenced modeling of building stocks and construction material flows. *Journal of Industrial Ecology*, 23, 253–267. DOI: https://doi.org/10.1111/jiec.12739

Heeren, N., Mutel, C. L., Steubing, B., Ostermeyer, Y., Wallbaum, H., & **Hellweg, S.** (2015). Environmental impact of buildings—What matters? *Environmental Science and Technology*, 49, 9832–9841. DOI: https://doi.org/10.1021/acs.est.5b01735

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & **Habert, G.** (2020). Biogenic carbon in buildings: A critical overview of LCA methods. *Buildings & Cities*, 1, 504–524. DOI: https://doi.org/10.5334/bc.46

ISO. (2021). *ISO 22156:2021: Bamboo structures—Bamboo culms—Structural design*. International Organization for Standardization (ISO). https://www.iso.org/standard/73831.html

ISO. (2022). *ISO 23478:2022: Bamboo structures—Engineered bamboo products—Test methods for determination of physical and mechanical properties*. International Standard Organisation (ISO). https://www.iso.org/standard/75683.html

Iqbal, Y., Lewandowski, I., Weinreich, A., Wippel, B., Pforte, B., Hadai, O., Tryboi, O., Spöttle, M., & **Peters, D.** (2016). *Maximising the yield of biomass from residues of agricultural crops and biomass from forestry* (Final Report). www.ecofys.com

King, C. (2020). Fighting climate change with bamboo. *China Dialogue*, October 29. https://chinadialogue.net/en/climate/fighting-climate-change-with-bamboo/.

Lapola, D. M., Martinelli, L. A., Peres, C. A., Ometto, J. P., Ferreira, M. E., Nobre, C. A., Aguiar, A. P. D., Bustamante, M. M. C., Cardoso, M. F., Costa, M. H., Joly, C. A., Leite, C. C., Moutinho, P., Sampaio, G., Strassburg, B. B. N., & **Vieira, I. C. G.** (2014). Pervasive transition of the Brazilian land-use system. *Nature Climate Change*, 4, 27–35. DOI: https://doi.org/10.1038/nclimate2056

Lesschen, J. P., Bakker, R., Elbersen, W., & **Poppens, R.** (2013). *Rice straw and wheat straw—Potential feedstocks for the biobased economy*. NL Agency—Ministry of Economic Affairs. https://english.rvo.nl/sites/default/files/2013/12/Straw%20report%20AgNL%20June%202013.pdf

Mishra, A., Humpenöder, F., Churkina, G., Reyer, C., Beier, F., Leon Bodirsky, B., Schellnhuber, H. J., Lotze-Campen, H., & **Popp, A.** (2022). Land use change and carbon emissions of a transformation to timber cities. *Nature Communications*, 13(1), 4889. DOI: https://doi.org/10.1038/s41467-022-32244-w

Page, B., Turan, G., Zapantis, A., Burrows, J., Consoli, C., Erikson, J., Havercroft, I., Kearns, D., Liu, H., Rassool, D., Tamme, E., Temple-Smith, E., & **Townsend, T.** (2020). *Global status of CCS report*. Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2020/11/Global-Status-of-CCS-Report-2020_FINAL.pdf

Pittau, F., Krause, F., Lumia, G., & **Habert, G.** (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, 129, 117–129. DOI: https://doi.org/10.1016/j.buildenv.2017.12.006

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., & **Habert, G.** (2019). Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *Journal of Cleaner Production*, 214, 365–376. DOI: https://doi.org/10.1016/j.jclepro.2018.12.304

Pomponi, F., Hart, J., Arehart, J. H., & **D'Amico, B.** (2020). Buildings as a global carbon sink? A reality check on feasibility limits. *One Earth*, 3, 157–161. DOI: https://doi.org/10.1016/j.oneear.2020.07.018

Powlson, D. S., Riche, A. B., Coleman, K., Glendining, M. J., & **Whitmore, A. P.** (2008). Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. *Waste Management*, 28(4), 741–746. DOI: https://doi.org/10.1016/j.wasman.2007.09.024

Puettmann, M. E., & **Wilson, J. B.** (2006). Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. *Wood Fiber Science*, 18–29. https://wfs.swst.org/index.php/wfs/article/view/1268

Raven, P., Berry, S., Cramer, W., Creutzig, F., Duffy, P., Holtsmark, B., Kammen, D., Levin S., & **Lucht W.** (2021). *Letter regarding use of forests for bioenergy. Letter to President Biden, President von der Leyen, President Michel, Prime Minister Suga, and President Moon (Policy Brief)*. Woodwell Climate Research Center. https://www.woodwellclimate.org/letter-regarding-use-of-forests-for-bioenergy/

Read, P., & **Denniss, R.** (2020). With costs approaching $100 billion, the fires are Australia's costliest natural disaster. *The Conversation*. https://theconversation.com/with-costs-approaching-100-billion-the-fires-are-australias-costliest-natural-disaster-129433

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & **Passer, A.** (2020). Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation. *Applied Energy*, 258, 114107. DOI: https://doi.org/10.1016/j.apenergy.2019.114107

Sathre, R., & **O'Connor, J.** (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy*, 13, 104–114. DOI: https://doi.org/10.1016/j.envsci.2009.12.005

Scarlat, N., Dallemand, J.-F., Taylor, N., Banja, M., Sanchez Lopez, J., & **Avraamides, M.** (2019). *Brief on biomass for energy in the European Union | EU Science Hub*. EC Publication. https://ec.europa.eu/knowledge4policy/bioeconomy%0AContact:%0Ahttps://ec.europa.eu/jrc/en/publication/brochures-leaflets/brief-biomass-energy-european-union

Scarlat, N., Martinov, M., & **Dallemand, J. F.** (2010). Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Management*, 30(10), 1889–1897. DOI: https://doi.org/10.1016/j.wasman.2010.04.016

Seppälä, J., Heinonen, T., Pukkala, T., Kilpeläinen, A., Mattila T., Myllyviita, T., Asikainen, A., & **Peltola, H.** (2019). Effect of increased wood harvesting and utilization on required greenhouse gas displacement factors of wood-based products and fuels. *Journal of Environmental Management*, 247, 580–587. DOI: https://doi.org/10.1016/j.jenvman.2019.06.031

Simpson, K., Janda, K. B., & **Owen, A.** (2020). Preparing 'middle actors' to deliver zero-carbon building transitions. *Buildings & Cities*, 1, 610–624. DOI: https://doi.org/10.5334/bc.53

Soimakallio, S., Kalliokoski, T., Lehtonen, A., & **Salminen, O.** (2021). On the trade-offs and synergies between forest carbon sequestration and substitution. *Mitigation and Adaptation Strategies for Global Change*, 26, art. 4. DOI: https://doi.org/10.1007/s11027-021-09942-9

Steffens, G. (2018). Changing climate forces desperate Guatemalans to migrate. *National Geographic*. https://www.nationalgeographic.com/environment/article/drought-climate-change-force-guatemalans-migrate-to-us

UNDESA. (2018). *World urbanization prospects: The 2018 revision, online edition*. United Nations, Department of Economic and Social Affairs (UNDESA), Population Division. https://esa.un.org/unpd/wup/Publications

UNEP. (2022). *Global status report for buildings and construction. Towards a zero-emission, efficient and resilient buildings and construction sector*. United Nation Environment Programme (UNEP). https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

van der Lugt, P., & **Vogtländer, J. G.** (2015). *The environmental impact of industrial bamboo products—Life cycle assessment and carbon sequestration* (Technical Report No. 35). International Network for Bamboo and Rattan (INBAR).

Vernick, D. (2020). *3 Billion animals harmed by Australia's fires*. World Wide Fund for Nature (WWF). https://www.worldwildlife.org/stories/3-billion-animals-harmed-by-australia-s-fires

Xu, J., Xie, S., Han, A., Rao, R., Huang, G., Chen, X., Hu, J., Liu, Q., Yang, X., & **Zhang, L.** (2019). *Forest resources in China—The 9th National Forest Inventory*. National Forestry and Grassland Administration.

Zea Escamilla, E., Habert, G., Correal Daza, J. F., Archilla, H. F., Echeverry Fernández, J. S., & **Trujillo, D.** (2018). Industrial or traditional bamboo construction? Comparative life cycle assessment (LCA) of bamboo-based buildings. *Sustainability*, 10, 3096. DOI: https://doi.org/10.3390/su10093096

Zea Escamilla, E., Habert, G., & **Wohlmuth, E.** (2016). When CO_2 counts: Sustainability assessment of industrialized bamboo as an alternative for social housing programs in the Philippines. *Building and Environment*, 103, 44–53. DOI: https://doi.org/10.1016/j.buildenv.2016.04.003

TO CITE THIS ARTICLE:
Göswein, V., Arehart, J., Phan-huy, C., Pomponi, F., & Habert, G. (2022). Barriers and opportunities of fast-growing biobased material use in buildings. *Buildings and Cities*, 3(1), pp. 745–755. DOI: https://doi.org/10.5334/bc.254

Submitted: 24 May 2022
Accepted: 11 September 2022
Published: 06 October 2022