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Wood in buildings: the right answer to the wrong question

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Wood in buildings: the right answer to the wrong question

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Abstract. Reducing the embodied emissions of materials for new construction and renovation of buildings is a key challenge for climate change mitigation around the world. However, as simply reducing emissions is not sufficient to meet the climate targets, using bio-based materials seems the only feasible choice as it permits carbon storage in buildings. Various studies have shown that bio-based materials allow turning overall life cycle impacts negative, therefore, having a cooling effect on the climate. In recent years, scholars and policy makers have focused almost exclusively on the advancement of wooden buildings. Timber structures stand out as they can be prefabricated and used for high-rise buildings. Yet, one important aspect seems to be overlooked: the consideration of supply and demand. Large forest areas that allow sustainable sourcing of woody biomass only exist in the Northern hemisphere, notably in North America and Europe. In these regions, though, urbanization rates are mostly stagnating, meaning new construction rates are low. The largest amount of material requirements in these regions are derived from the refurbishment of the existing stock. Moreover, in areas where structural material is needed for new construction, in Asia, Africa and South America, rain forests need to be protected. Therefore, we need to rethink the desire to find one solution and carelessly implement it everywhere. Instead, we need to consider locally available material and know-how for grounded material choices. This paper explores the supply of a range of bio-based materials and matches it against the material demand of global building stocks. It is based on various previous studies by the authors, of South Africa, China, Portugal, and more. The analysis divides between structural materials for new construction, such as wood and bamboo, and thermal insulation materials for the refurbishment of existing buildings, such as straw and hemp. The results emphasize the need for diversifying bio-based material solutions.

Keywords. Bio-based, Carbon Storage, Straw, Bamboo, Resource Availability

1. Introduction

Buildings and the construction industry are responsible for circa 40% of global final energy use and energy- and process-related emissions [1]. It is clear that the building sector will have to play a key role in achieving global climate change targets until 2050 and beyond, yet, the challenge ahead is big: on the one hand, an additional 76 billion m^2 of floor area will be needed until 2060 globally [2], and, on the other hand, the construction industry is particularly inert to innovation [3]. While until some years ago, policy and research focused on the impacts arising during the operation of a building [4], it was shown that embodied impacts of building are increasing in relative terms over the life cycle since an increased energy efficiency of buildings reduces the operational impacts [5], and in total terms in new and advanced residential construction [6]. In this sense, the choice of material is ever more relevant than the building's operation. Thus, a critical question arises: which construction material allows to achieve the ambitious target of a climate neutral built environment by 2050 at the global scale?

Construction materials made with biomass allow temporary carbon storage and therefore, provide an opportunity for climate neutral buildings. The stored carbon is only released back to the atmosphere at the end of life of the building element, if not reused or recycled. If used correctly, bio-based construction products and systems can achieve similar performance values as conventional counterparts. However, so far, bio-based construction has been largely overlooked, with the sole exception of timber. Timber construction has many advantages, among them its regenerative character, and the high level of digitalization and fabrication. Thanks to these development and new regulations the practical application of timber in mid and high-rise buildings are becoming more common. There is a large group of scientists [7] who advocate that engineered timber could be used to turn the global building stock into a carbon sink, as a possible remedy for the climate crisis. However, this idea is problematic when considering the spatial mismatch between sustainable timber supply and building stock demand.

One of the main socio-economic drivers of urban development is population growth. Figure 1 shows, on the bottom, a global a map of projected population in 2100. The biggest increase of population is expected to take place in Africa and Asia. Asia's population is expected to peak at 5.4 billion people around 2055, while Africa's population is expected to keep on growing and to reach 10.9 billion people in 2100. Also, on the upper part of Figure 1, we can observe the existing global forest distribution and proportion in 2020 are illustrated. When comparing these two maps, it becomes clear that there will be a mismatch: 45% of global forests are tropical forest. These are located mainly in South America, Africa and South-East Asia. As rain forests are already threatened by deforestation and the impacts of climate change, these are forests areas that should not be put under pressure from the bioeconomy.

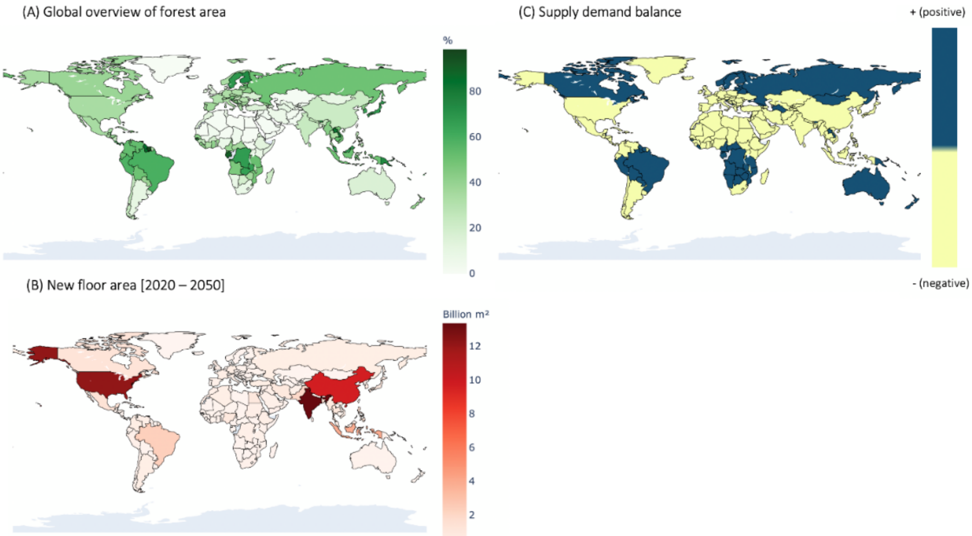

Figure 1. Global comparison of supply and demand for timber-based floor area. Image taken from [8].

Moreover, when thinking about which type of construction activities will dominate the built environment evolution in the different regions, another mismatch becomes apparent: due to increasing population in Africa and Asia, large amounts of structural materials, for example engineered timber, will be required for new construction of houses. However, in the global North, most of the building stock already exists but needs retrofit. Furthermore, in Europe it is estimated that three quarters of the building stock are energy-inefficient [9]. In North America and Europe, large forest areas would allow sustainable sourcing of woody the largest amount of material requirements in these regions are derived from the refurbishment of the existing stock. Therefore, it seems clear that timber will not be the only construction material to achieve a climate neutral building stock until 2050 at the global scale.

This paper wants to make a statement for other types of bio-based construction materials beside timber, which provide a variety of material choices that together offer a more robust and sustainable path on the way to a global carbon neutral building stock.

2. Organization of the paper

This paper is a synthesis of previous work by the authors. The goal is to explore the supply of a range of bio-based materials and to analyze them in the local context considering local raw material supply and building stock needs regarding future construction and renovation.

The next section is divided in three parts that each present results and discusses them. Firstly, the potential carbon storage and fossil emission of different bio-based construction materials are compared at the product scale. Secondly, two promising bio-based materials are selected, and their biomass availability is compared with the building stock demand at the global scale. Thirdly, additional niche applications of bio-based materials are presented that optimize the local context and challenges.

3. Results and discussion

3.1. Comparison at the material level

Table 1 shows a selection of bio-based construction products. It is a non-exhaustive list, which gives an idea of the large amount of bio-based construction options. Many are available on the market and have been proven feasible at the large scale. The table divides by biomass and lists carbon storage and rotation period of the biomass, typical construction products and their use type and purpose. The type distinguishes between structural and insulating material, and the purpose notes common applications, e.g. thermal or acoustic insulation. The carbon content of the different biomaterials is similar: seaweed has the lowest value that is 0.35 kg C per kg of biomass, woody biomass has 0.5, and cork has the highest carbon content that is 0.55. A more significant difference is the rotation period of the different plants, which defines the time a new plant needs to grow to reach harvest maturity. This is important as the carbon benefit of bio-based construction is not the transfer of biogenic carbon from nature to the building stock, but the new plant that replaces the harvested plant and that sequesters extra carbon from the atmosphere. The rotation period of trees is decades long (between 40 to 90 years), yet the time to fight the climate crisis is running out. Therefore, materials like hemp and straw that can be harvested yearly are more promising.

Figure 2 analyzes the carbon storage potential over time considering rotation period and fossil emissions in more detail. The figure compares embodied (EN 15978 modules A1-A5) fossil fuel emissions and GWP_{bio} credit given for two different periods (30 and 60 years) that the material (and biogenic carbon) is potentially stored in the anthroposphere. Data for fossil fuel emissions are taken from Ecoinvent and based on previous work [21–24]. The values for carbon storage credit are calculated with the GWP_{bio} factors from Guest *et al*. [25]. The longer the storage period, the more credit is realized, since more of the harvested biomass can be regrown. Straw has the lowest embodied fossil emissions (1.37 kg CO_2 eq. m^2 of floor area). Over a short storage period of 30 years, the biogenic carbon storage potential of sawnwood is the only positive (0.075 kg of C per kg of material). The reason is the long rotation period to recover the harvested tree (90 years).

Table 1. A selection of bio-based construction products.

Material	Carbon: $\frac{\text{kg C}}{\text{kg biomass}}$	Carbon: Reference	Rotation period: Years	Rotation period: Assumption & source	Product	Type & purpose: Structural	Type & purpose: Insulating
Moso bamboo	0.5	[10]	5	Range 3-8 years [11]	Bamboo pole, flattened bamboo	Frame	
					Glue-laminated (Glulam) bamboo	Frame	
					Cross-laminated bamboo (CLB)	Ceilings, walls	
Cork	0.55	[12]	9	Min. allowed rotation period [13]	Insulation cork board (ICB)		Thermal/Acoustic
					Granulate		Acoustic
Hemp	0.5	[14]	1	Assumption - annual crop	Hempcrete (shives with lime-based binder)	Masonry infill	Thermal
					Hemp wool with hemp fibres		Thermal
Palm leaves	0.48	[15]	1	Assumption - annual crop	Fibres from oil or date palms		Thermal
Seaweed	0.35	[16]	1	Marine macrophytes [16]	Thatch panels		Thermal
Straw	0.4	[17]	1	Assumption - annual crop	Strawbales	Loadbearing or infill	Thermal
					Light clay straw	Infill	Thermal/Acoustic
					Straw chips		Thermal
Timber	0.5	[18]	40	Pacific Northwest Doug-Fir larch [19]	Glulam, Laminated veneer lumber (LVL), Cross laminated timber (CLT)	Skeleton / frame	
			90	Central European Spruce [20]	Solid logs/boards	Loadbearing	
					Softwood fibre boards		Thermal/Acoustic
					Bulk woodchips		Thermal/Acoustic

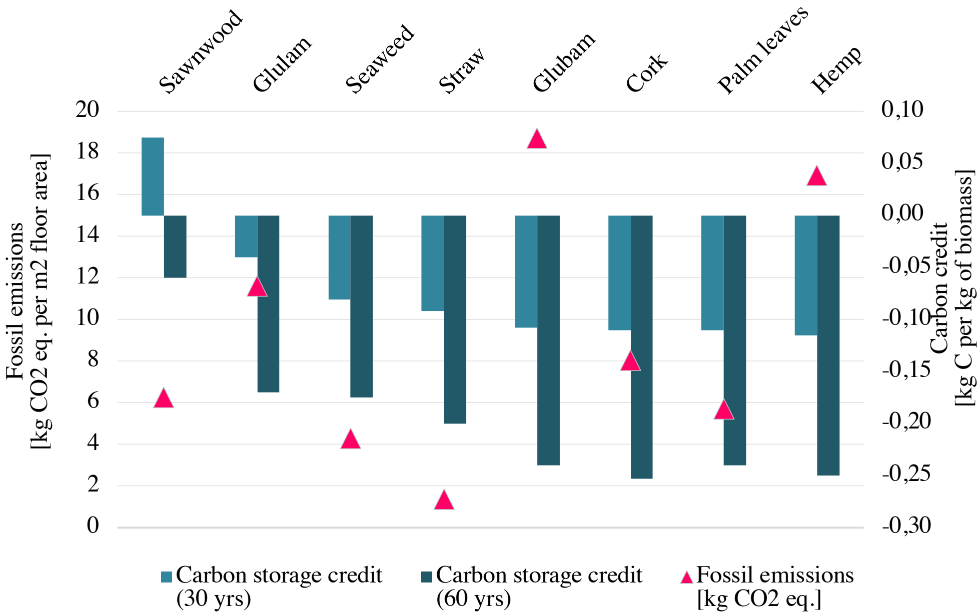

Figure 2. Comparison of embodied CO_2 emissions vs. temporary carbon storage credit in buildings.

3.2. Matching supply and demand

In this section the potential large-scale supply of two materials, bamboo and straw, is compared to the forecasted demand of geoclusters around the world. Bamboo and straw were chosen as they seem particularly promising to be implemented at the large scale: bamboo is a very fast-growing type of grass that can be used as a structural building for high-rise buildings. It has similar qualities to timber, yet bamboo forests are endemic to Asia and South America, where urbanization rates and, therefore, new construction rates are high. Straw is an agricultural by-product that can be harvested every year. It has great thermal insulating capacities and is available in large quantities in Europe and the US, where large amounts of thermal insulation material will be needed.

Table 2 summarizes the projected new floor area and renovated floor area. The values for floor area growth are taken from Güneralp *et al.* [2], considering the S50 (medium urban population density) scenario for 2010 to 2050. The values for renovated floor area are derived from [2]. It is assumed that there will only be thermal retrofit in the Global North (i.e. EEU, FSU, WEU, NAM) and in POECD, with a 3% renovation rate based on targets set by regulatory agencies to achieve climate neutrality [26]. In the remaining geoclusters of the Global South (CPA, LAC, SSA, MNA, PAS, SAS) 0% renovation is assumed. The table also shows values for yearly available biomass for bamboo and straw. Values are taken from [27,28] and [29,30], respectively. Please note that while for straw intersectoral competition is considered, for bamboo, due to a lack of data, it is assumed that 25% of the sustainably harvested biomass could be used for construction. The values in bold blue font highlight high demand from the building stock and high supply of biomass. For example, a previous study by the authors [31] found that the available straw in the EU-28 countries (roughly referring to EEU and WEU geoclusters) provides more than enough material. In fact, only 12% of the currently available straw for construction (referring to already used straw in construction and “leftover” straw that is currently not used by any sector) would be needed to meet the material demand for current renovation rates in the EU-28 (circa 1% yearly).

Looking at CPA, 23.84 Mio. tons of bamboo are available yearly in this geocluster. Assuming a constant supply, this means that from 2010 to 2050, 953.6 Mio. tons of bamboo are available. The amount of floor area that could be constructed, using bamboo, depends on the type of product and production efficiency and should be further investigated. However, to give a rough estimate, and using values from [32], the efficiency coefficient to transform fresh bamboo into engineered bamboo can be obtained as 10.5%. Subsequently, the available 953.6 Mio. tons would produce 100.13 Mio. t of engineered bamboo. Assuming a material coefficient of 126 kg bamboo per m^2 floor area [33], this gives 0.80 Billion m^2, or circa 5% of the projected 15.66 billion m^2 could be constructed using engineered bamboo. Even though only a small relative share, it represents a significant amount of material and therefore, possible reduction of CO_2 and increase of carbon storage in the CPA building stock.

Table 2. Building stock growth (data from [2]) and selection of available biomass.

Geocluster		New construction: Floor area growth until 2050 [2] [%]	New construction: Floor area growth until 2050 [2] [Billion m^2]	New construction: Available bamboo [10^6 t/y]	Thermal retrofit: Yearly renovation [%]	Thermal retrofit: Renovated floor area [Billion m^2]	Thermal retrofit: Available straw [10^6 t/y]
EEU	Central and Eastern Europe	16%	0.56	0	3%	**0.13**	**56.26**
FSU	Independent states of former Soviet Union	17%	1.52	0	3%	**0.32**	**21.23**
WEU	Western Europe	20%	5.41	0	3%	**0.98**	**57.71**
POECD	Pacific OECD	25%	1.54	0	3%	**0.23**	**42.53**
CPA	Centrally planned Asia and China	30%	**15.66**	**23.84**	0%	0	6.42
NAM	North America	64%	17.45	0	3%	**1.34**	**23.30**
LAC	Latin America and the Caribbean	64%	9.67	0.35	0%	0	0.16
SSA	Sub-Saharan Africa	66%	**6.91**	**16.41**	0%	0	24.91
MNA	Middle East and North Africa	87%	7.40	0	0%	0	121.25
PAS	Other Pacific Asia	90%	**11.91**	**18.47**	0%	0	96.67
SAS	South Asia	119%	**22.94**	**32.48**	0%	0	54.12

3.3. Context-specific material alternatives

This section has a closer look at two bio-based construction products, insulation cork board used for thermal insulation in Portugal, and a concrete alternative made with binder and wood chips from invasive alien plants in South Africa. These are two examples of specific material solutions, that context-specific, considering local needs and material availability of raw material, offer great potential for building stocks.

3.3.1. Insulation cork board (ICB) in Portugal. Cork is a valuable material that is mainly used in the wine industry for bottle cork stoppers but also has great potential as an insulation material thanks to its natural resin. Expanded cork agglomerate is 100% natural. Cork is harvested from cork oaks that only grow around the Mediterranean. Portugal is the world's biggest producer of cork. Figure 3 visualizes cork cultivation in the EU28 and puts it in context with the available and required land for producing ICB used in buildings. While at the European level, ICB could only meet 2% of the building stock demand, however, locally in Portugal the supply exceeds the demand 10-fold. For more information, please refer to a previous study by the authors [31].

In 10^3 ha	**EU-28**	**Portugal**
Available land for all sectors	1'500	730
Available land for construction	450	218
Land demand for construction	20'450	21
Supply/demand	2%	1024%

Figure 3. Comparison of available land for cork cultivation in EU-28 and Portugal (table) and visualization of cork forests in EU-28 (map). Data taken from Göswein *et al.* [31]

3.3.2. A concrete alternative made with wood chips made from invasive alien plants (IAP) in South Africa. South Africa is facing the challenge of circa 160 Mio. hectare land that is invaded by alien plants. Here, IAP, such as *Eucalyptus, Acacia,* and *Pinus,* reduce water runoff and threaten endemic species. Moreover, these types of trees are prone to wildfires, which is not only a hazard but also releases sequestered biogenic carbon to the atmosphere, thereby contributing to increased greenhouse gas (GHG) emissions. There is no limit in the foreseeable future to the vast and ever-increasing amounts of available invasive biomass. However, value added products can provide an economically feasible path to combat IAP. A new type of concrete from South Africa called *nonCrete*, made with binder and wood chips from IAP, is a VAP that potentially can allow for multi-dimensional benefits: it can lead to the clearance of invaded land, thereby reducing water scarcity and GHG emissions, creating jobs in local communities, and if used properly, it can provide an affordable and sustainable building material. The data presented in 4 is taken from a previous study by the authors *[34]*. It compares two scenarios for the embodied emissions of Cape Town's residential building stock. The study was based on census data from 2011. Back then the building stock corresponded to $3.09 * 10^7$ t of CO_2 eq. embodied emissions. Assuming the same types of conventional construction materials and practices will be used in the future, this could amount to $6.87 * 10^7$ tCO_2 eq. in 2050. However, using *nonCrete* made with IAP wood chips, could reduce the fossil emissions to $5.41 * 10^7$ tCO_2 eq. plus an additional (-)$1.7 * 10^7$ tCO_2 eq. of biogenic carbon emission from wildfires could be saved. This is a very particular example, yet, invasive alien plants are a problem around the world, for example in Kenya, New Zealand and Chile, which are countries that battle their own set of IAP species.

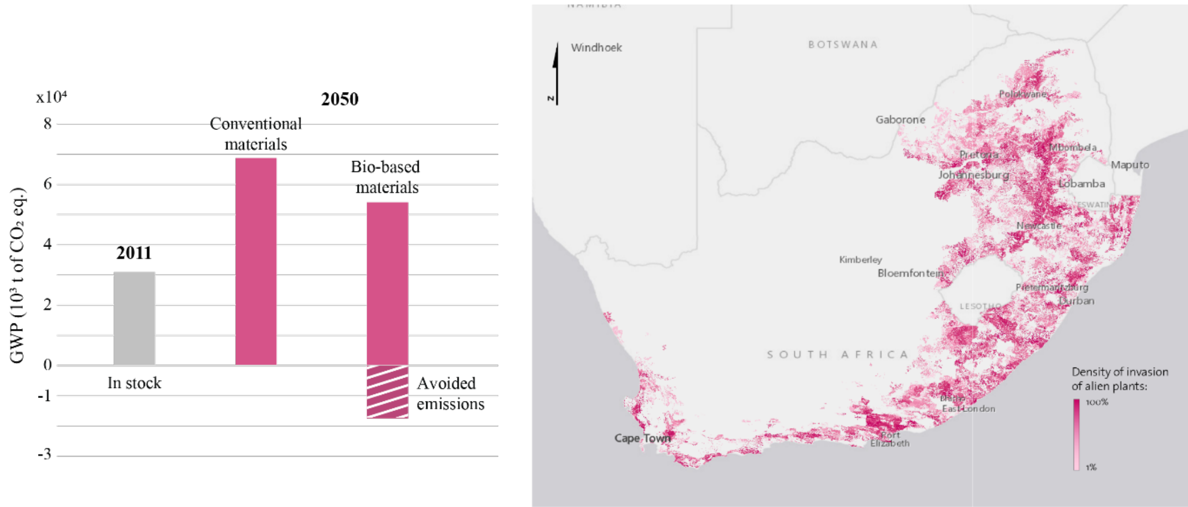

Figure 4. Comparison of GWP for two material scenarios in 2050 in Cape Town (bar chart) and visualization of IAP density in South Africa. Data taken from [34] and [35] respectively.

4. Conclusions

Timber construction offers a wide range of applications and opportunities to solve the challenges faced on the built environment. The use of timber in construction provides several benefits, as it is a natural material that can be prefabricated, it has great load-bearing capacities and can, therefore, be used for low-mid- and high-rise buildings. However, it is important to highlight that these are hindered by many factors including local regulations, material availability and maturity of the market and industry on a specific country. Furthermore, timber cannot be considered as the only solution to answer the question of how to sustainably develop a carbon neutral built environment. There simply is not enough timber available from sustainable production in locations where structural material will be required in large quantities. Since the amount of sustainably sourced biomass, particularly of wood, is limited, the question should not be how to achieve a global roll-out of timber construction but instead how to use the limited biomass supply wisely: for food, then for buildings, and then energy. And for buildings, the substitution of fossil materials with high embodied emissions should be prioritized.

Therefore, we suggest extending the idea of wood-construction to bio-based construction, considering a range of biomass options. These materials are different in their structural and insulating capacities as well as their raw material availability, but it is exactly these differences that make them stand out on the construction material palette, thereby offering a feasible pathway on the way to a carbon neutral building stock.

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