How Much Carbon Can Construction Materials Store?

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Motivation

Background

39% of annual global greenhouse emissions are attributed to the built environment [1]. To address global temperature rise, attributed to the release of greenhouse gasses, sources must be reduced, and sinks augmented. The built environment has long been considered a significant contributor of greenhouse emissions due to energy consumption during operation, and production of construction materials. Yet, some construction materials, such as timber products and fast-growing grasses, also store carbon. A new paradigm has begun to emerge that evaluates buildings not only for their life cycle carbon emissions (i.e., whole-life carbon), but also for their potential to store and sequester carbon. The transition to post-carbon cities will require the use of carbon storing materials due to both their storage potential and reduced life cycle carbon emissions. It has been estimated that between 0.15 and 4.99 Gt CO_2e per year can be stored in buildings between 2020 and 2050 with aggressive adoption of bio-based structural materials [2].

Materials and Carbon Storage

There are two primary mechanisms for storing carbon in construction materials: photosynthesis, and *in-situ* carbonation of cementitious materials. Other mechanisms have been described, such as accelerate carbonation of cementitious materials, and carbon dioxide utilization in aggregate production, yet these mechanisms are outside the scope of the present analysis, due to a lack of market penetration.

Biogenic Carbon Storage

Materials derived from bio-based sources, rely on photosynthesis to sequester carbon from the atmosphere. Carbon is stored in various forms within bio-based materials, typically in cellulose which is the primary product of photosynthesis. Cellulose commonly represents, by weight, 40-50% of wood and up to 80% of grasses such as flax and hemp.

Cementitious Carbon Storage

Cementitious materials contain hydration products which react with carbon dioxide to produce calcium carbonate. Cement is the most widely used construction material, and, it can sequester significant quantities of CO_2. For instance, it was estimated that in 2013, 0.92 Gt of CO_2 were absorbed by cement stocks globally [3]. For a full discussion of the mechanism of carbon storage, see the two models proposed by Souto-Martinez et al. 2017 [4] and Pade & Guimaraes 2007 [5].

Materials

Dimensioned Lumber refers to solid wood products cut to specified dimensions for use as structural timber. These products store carbon through biogenic uptake.

Engineered Timber includes a variety of wood-based technologies, including plywood, oriented strand board, glulam, cross laminated timber, laminated veneer lumber, and many more. Engineered timbers typically have higher cradle-to-gate emissions compared to dimensioned lumber on a declared unit basis, but also store carbon as they are timber-based materials.

Ordinary Portland Cement (OPC) is the second most commonly used material in the world and is used in a variety of construction systems, including reinforced concrete and mortar. While OPC generates significant cradle-to-gate emissions, it recovers some of those emissions while in service through carbonation.

Straw can be compressed into bales to make a building envelope that has beneficial structural and insulative properties. Due to its fast-growing cycle, including biogenic carbon uptake, straw bale construction is an attractive carbon storing construction system.

Cellulose insulation uses cellulose-based materials to insulate building envelopes. It has favorable thermal properties in addition to being carbon-storing in comparison to foam or fiberglass alternatives.

Vegetal Concretes are a broad class of fiber-composite materials. They are a light-weight concrete using bio-based materials (e.g., hemp, rice husk ash, sunflower, flax, etc.) as aggregate with a cementitious binding material. Carbon storage mechanisms include both biogenic uptake and carbonation. The most common plant aggregate used is hemp, often referred to as "hempcrete".

Cork is another insulation material which is renewably harvested bark, containing stored carbon, from cork oak trees.

Bamboo is an emerging carbon-storing material that can be used both in its pole form or engineered like engineered timbers. Bamboo is grown around the world, making it well suited for local design solutions.

Accounting Methods

Life Cycle Assessment

Life cycle assessment (LCA) is a methodology used to account for the inputs and outputs between a system and the environment. LCA can be applied at a variety of scales, from a material sub-system, to a whole building. Due to the immediate global need to reduce greenhouse gas emissions to avoid global temperature rise, carbon emissions (referring to all greenhouse gas emissions) are commonly the only input and output accounted for between a building system and the environment. The release of carbon emissions results in a time-specific warming potential for the world. For example, the midpoint indicator, 100-year global warming potential (GWP100) is a commonly used metric. When accounting for both the emissions, and uptake of carbon-storing materials, special consideration must be given to the time at which the carbon was emitted or absorbed. The following section describes the three common methods for accounting for carbon storage of materials. For a full discussion of the approaches, see a recent review by Breton et al. 2018 [6].

Traditional Static LCA

The first, static LCA, either ignores the carbon uptake from a material under the assumption that no long-term carbon storage (e.g., more than 300 years) will occur, or reports the carbon uptake separately for inclusion or exclusion by the practitioner. Excluding carbon uptake is the most conservative, while including it is the least conservative. Due to its simplistic approach, traditional static LCA does not fully account for the potential environmental benefit of using carbon-storing materials.

Dynamic LCA

The second approach, Dynamic LCA, captures the time-sensitive nature of carbon emissions, making it well-suited for considering construction materials with both uptake and emissions occurring at different points in a 100-plus year lifespan. Dynamic LCA relies upon dynamic life cycle inventories, which account for the annual emissions or uptake of carbon over the system's lifespan. These inventories are then coupled with a greenhouse gas' dynamic characterization factor (DCF), which is defined as the cumulative radiative forcing per unit mass of greenhouse released in the atmosphere since the emission to calculate the global warming impact (GWI). The following equations describe the accounting methodology, adapted from Levasseur et al. 2010 [7].

$$DCF_i(t)_{instantaneous} = \int_{t-1}^{t} a_i[C_i(t)]\,dt$$

$$GWI_{inst}(t) = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^{t} [g_i]_j * [DCF_i]_{t-j}$$

$$GWI_{cum}(t) = \sum_{j=0}^{t} GWI_{inst}(j)$$

DCF_i = dynamic characterization factor for greenhouse gas i (e.g., CO_2, CH_4, etc.)
t = time
a_i = radiative efficiency of greenhouse gas i
$C_i(t)$ = residual concentration of greenhouse gas i in the atmosphere after a pulse emission
g_i = life cycle inventory for each year j

When applying this dynamic methodology to carbon-storing systems, the end of life assumptions and time horizon have significant impact on the results [8]. These two variables are often chosen at the discretion of the LCA practitioner, and influence the dynamic lifecycle inventory, .

Dynamic Global Warming Potential

The third approach to accounting for the carbon uptake of materials is a hybrid, metric-based approach, between the two previously described approaches. A time-dependent characterization factor is used to determine a dynamic global warming potential (GWP_{dyn}) [9, 10]. GWP_{dyn} is a generalized form of biogenic global warming potential (GWP_{bio}), taking into account how the time of emissions and uptake has an effect on the climate's warming potential. For example, in the context of biogenic carbon, the metric considers how the removal of forest products in the form of construction materials and regrowth of a forest or crop contributes to the greenhouse gas balance. For a forest with a short rotation time, the removal of carbon, can be replaced more quickly, thus a lower GWP_{dyn} value is achieved. A negative GWP_{dyn} represents net carbon storage over the considered time horizon, recognizing that end-of-life scenarios greatly impact the total greenhouse gas balance. For pulse emissions, typical for the production of construction materials, accounting for carbon using GWP_{dyn} is equivalent to using the traditional LCA approach. Yet, for systems that have a distributed emissions profile (such as timber products), the computed GWP_{dyn} can be negative (i.e., net carbon storage) in comparison to the static approach which might have ignored the temporary storage of biogenic carbon.

From a long-term perspective, the carbon stored temporarily in construction materials will one day progress along the global carbon cycle. Thus, there is a view that no benefit should be given to the stored carbon. However, due to the short-term demand for construction materials attributed to urbanization and population growth coupled with the aggressive reductions required to keep global temperature rise to less than 2°C, another view is that carbon storage in construction materials should be promoted. As the built environment transitions towards a circular economy, carbon stored in construction materials will be stored for more than a single building lifespan. Thus, there is the potential for carbon storage in buildings to become more permanent.

Carbon Storage Potential

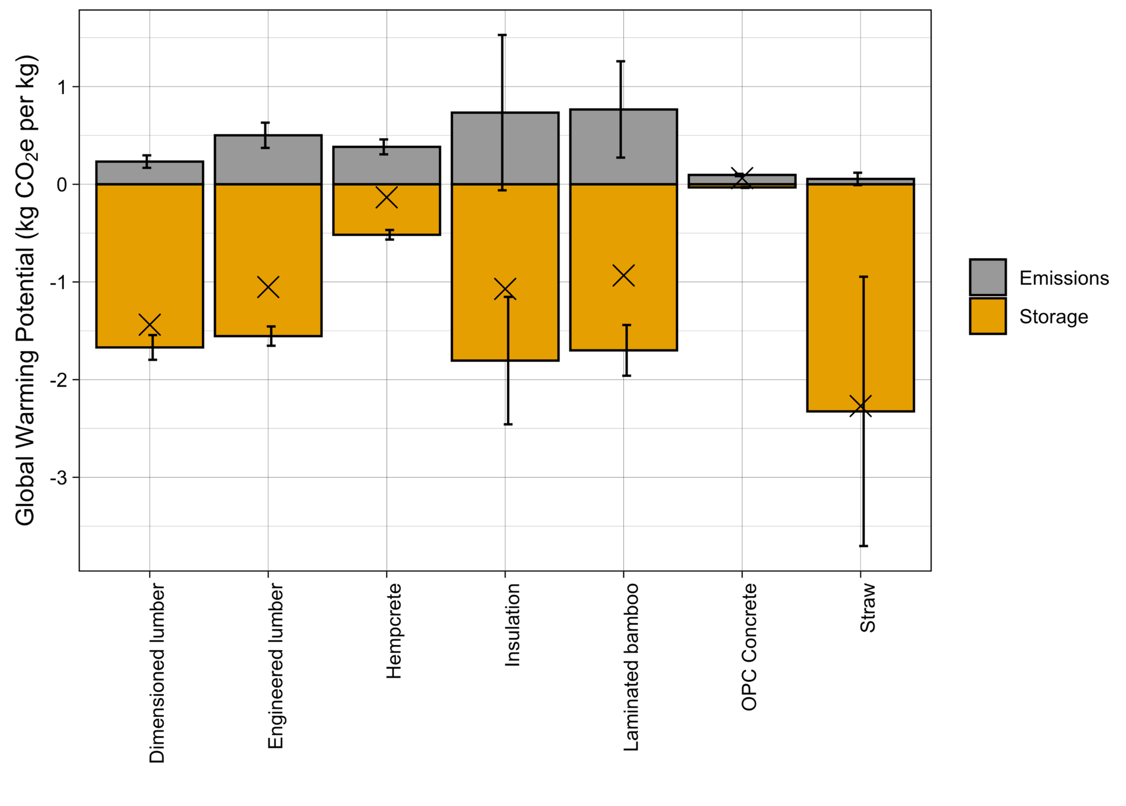

Figure 1. Carbon emissions (in gray) compared to carbon storage potential (yellow) of various construction materials. Error bars represent the standard deviations for the data collected, while crosses (X) represent the net cradle-to-gate emissions when carbon storage is considered (for the mean values). Cradle-to-gate emissions are shown for a declared unit of 1kg.

There is variation between the cradle-to-gate emissions of carbon storing construction materials in addition to the carbon storage potential of each. Figure 1 shows the emissions and storage of various materials for a declared unit of 1kg. Comparison between materials is not illustrated through this figure, since the declared unit does not represent a functional use within a building. Instead, the variation within a material is shown. When using static LCA to account for carbon storage, all bio-based materials are net carbon storing, while ordinary portland cement (OPC) concrete has net positive emissions. Figure 2 shows the comparison of the carbon storage results between the static accounting methodology and the dynamic global warming potential methodology. The GWP_{bio} method results in a lower GWP for all biogenic materials, regardless of building service life. The use of carbon storing materials reduces significantly when the materials are stored for 60 years, rather than 100 years. This result highlights how the choice of accounting methodology has significant impact on the result and how extending building lifetime is necessary to consider construction materials as being carbon storing.

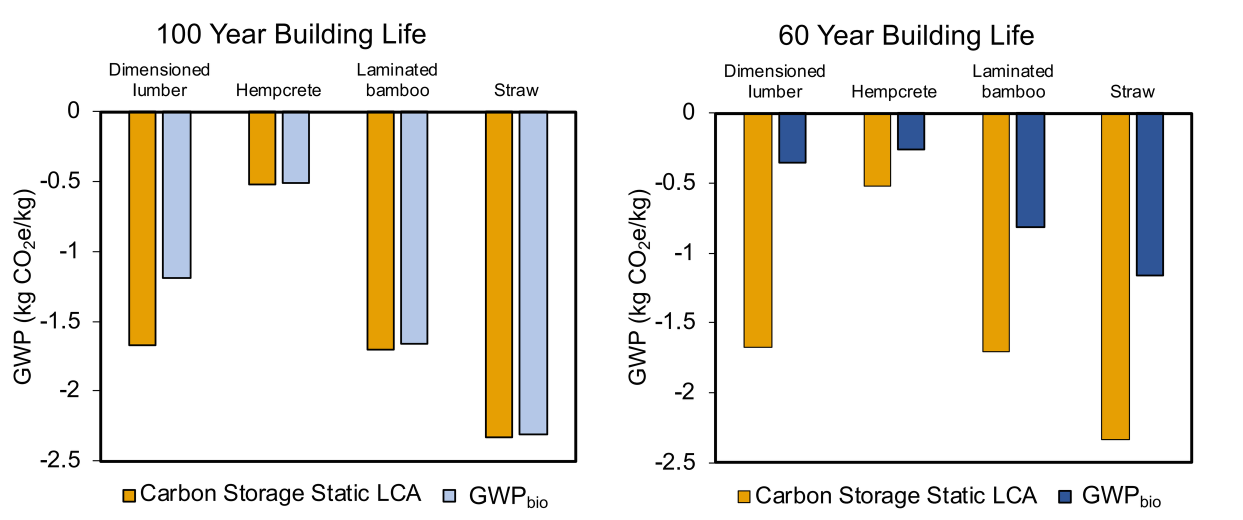

Figure 2. Carbon storage potential of materials using biogenic uptake during cradle-to-gate (yellow), equivalent values in Figure 1, compared to adjusted values using a dynamic consideration of GWP_{bio} as described by [10]. Rotation times for dimensioned lumber, hemp, bamboo, and straw are 70, 1, 5, and 1 year(s) respectively. A comparison between these accounting methods and dynamic LCA were not included due to the complexities that arise from dynamic LCA. Yet, the expected result is similar to the results shown here.

Future Work

There is a grand opportunity for carbon to be stored in construction materials. Yet, in order for this carbon storage to be realized, forests and crops must be managed properly, materials must be stored in buildings for extended periods of time and be integrated into a circular economy at their end of life. While there are many success stories of carbon storage being successful at the building scale, there are few studies that evaluate the potential global demand for carbon storing materials. If carbon is to be stored in buildings by choosing biogenic carbon-based construction materials, there should be a local supply to meet the demand.

Furthermore, building designers typically ignore carbon storage in buildings due to the uncertainties associated with accounting for biogenic carbon. Dynamic LCA and dynamic global warming potential accounting methodologies are not currently integrated into existing design tools. The flexibility of these tools to capture the nuances of carbon storage such as forest management and end-of-life scenarios makes them well suited for use by building LCA practitioners. To fully realize their potential, these methodologies should be integrated into existing design tools such that building designers can design not only to reducing whole life carbon, but also optimize for carbon storage.

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