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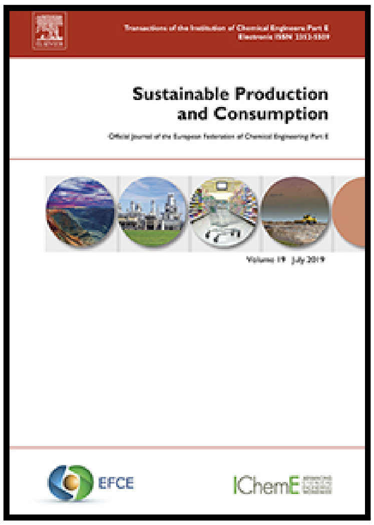

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Carbon Sequestration and Storage in the Built Environment

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Abstract

The increasing interest in bio-based construction materials has resulted in the emergence of the concept of "buildings as a carbon sink". Quantifying and comparing the effects of carbon sequestration and storage in buildings from a life cycle perspective involves the evaluation of flows and processes taking place at different timescales and across ecological, technological, and economic domains. This scoping review sheds light on the heterogeneous body of approaches and results from relevant scientific literature of the past decade: 180 articles were reviewed following a systematic search and relevance-checking process. Contributions are evaluated based on the scale of interest (material, building, building stock), the sequestration mechanism (photosynthesis, carbonation) and the accounting methodology adopted to quantify global warming. The majority of works taking a life cycle perspective adopt static methods, with only a few accounting for dynamic effects over time, although more recent studies do tend to recognise the need for dynamic life cycle assessment. A characterisation of current and future carbon storage in the global building stock is still needed, and substantial work remains to be done to validate the theory of buildings as a carbon sink to mitigate the effects of climate change. Reports on carbon stored in durable construction products and buildings mostly find cumulative effects that are less than emissions from fossil fuel use in a single year (ranging from negligible to 175%). Furthermore, net gains in storage in the built environment can be offset by net losses in forest carbon, and the benefits of substitution with wood are sometimes overstated. Further adoption of bio-based construction materials can – at best – only make a substantial contribution to climate change mitigation in the context of rapid global progress in decarbonisation.

Keywords: Biogenic carbon, bio-based construction materials, carbonation, harvested wood products.

1.0 Introduction

A new paradigm has emerged among building design practitioners and academics in which buildings are considered a carbon sink. This paradigm is a response to the need for humanity to reduce greenhouse gas (GHG) emissions and augment natural carbon sinks to limit global temperature rise (IPCC, 2018). In 2018, the built environment was responsible for 40% of global GHG emissions (IEA and UN Environment Programme, 2018). Yet more importantly, if no action is taken to reduce the rising demand for construction materials between 2008 and 2050, 35-60% of the available carbon budget to meet a 2°C target will be spent on constructing the built environment, not even including its operation (Müller et al., 2013).

A wealth of research has explored and quantified the sustainable production and consumption of construction materials, considering a life cycle approach, with a particular emphasis on climate change effects (Röck et al., 2020). Such work is frequently limited to the emissions associated with the extraction and manufacturing of such materials, and sometimes their end-of-life treatment. When comparing the emissions of materials, bio-based materials containing biogenic carbon typically have lower environmental impacts than others (Hill and Dibdiakova, 2016). There is, however, increasing awareness of the potential role that construction materials can play in mitigating climate change by sequestering and storing atmospheric carbon (Cao et al., 2020; Churkina et al., 2020; Pomponi et al., 2020; Xi et al., 2016). Carbon can be stored in bio-based construction materials, accumulating over decades prior to construction (*e.g.*, wood) or in just the previous year (*e.g.*, agricultural crop residues); carbon can also be sequestered and stored by cementitious materials (*e.g.*, concrete), after construction, through the process of carbonation. The challenges associated with the quantification and comparison of these effects in different materials – taking place over contrasting timescales – has been previously noted (Hill, 2019; Tellnes et al., 2017) but are still not universally understood or implemented.

At the material or assembly scale, contrasting methods exist for accounting for sequestered carbon (Hoxha et al., 2020; Liptow et al., 2018) resulting in potentially drastically different conclusions (Levasseur et al., 2013). At the landscape, regional or national scales, there is ongoing discussion about whether the "forest-wood products" system can successfully result in carbon storage, as argued by Härtl et al. (2017), or whether a more cautious approach is needed owing to the losses of forest carbon potentially outweighing the gains made in the wood product carbon pool (Soimakallio et al., 2016).

As the "buildings as a carbon sink" paradigm has gained traction, numerous studies have investigated the ways in which carbon is sequestered by construction materials, how carbon storage should be accounted for, and the ways in which buildings and building stocks can be a climate solution. This review aims to elucidate the ways in which the scientific literature has considered carbon sequestration and storage by construction materials in the past decade. The "buildings as a carbon sink" paradigm is evaluated at multiple scales: the material, the building, and the building stock. Focus is paid to materials which are already prevalent with significant market penetration, while novel materials have been excluded. A systematic methodology is taken, which is described in **Section 2**. **Section 3** describes the ways in which carbon sequestration and subsequent storage is achieved, **Section 4** briefly reviews the different methodologies developed to account for carbon storage, **Sections 5, 6**, and **7** explore carbon storage at different scales, while **Section 8** provides concluding remarks and an outlook on future research.

2.0 Review Methodology

To evaluate how, and to what extent, carbon is stored in the built environment, we perform a scoping review of the literature using predefined search terms, as illustrated in **Figure 1**. We limit the scope of this review to peer-reviewed journal articles, published between 1 January, 2010 and 1 June, 2020. Other review papers were not included in the primary analysis but are referenced where appropriate. The search terms used, as described in **Table 1**, are derived from three types of words: (i) the scale at which carbon storage is identified, (ii) the mechanism through which carbon is stored, and (iii) the accounting methodology used to quantify the carbon stored. Adjectives were added to the three primary scales to capture the range of terminology used to refer to construction and building materials. We generated unique combinations (with loose or approximate phrases) of the terms, using boolean '*OR*' and '*AND*' operations where appropriate to create 504 queries. These queries generated 3,275 results when duplicate entries were removed. For a summary of all queries searched and the number of results for each, see the **Supplementary Data**. To automate the query process, we use the `elsapy` Scopus API with Python 3 (*elsapy*, 2019).

From the initial collection of search terms, we refined the 3,275 results to 175 articles, based upon the pertinence of (1) the title, (2) the abstract, and (3) the article itself. If an article title, or abstract was ambiguous, it was moved forward in the selection process and only rejected if it failed to match the focus of the present review. As shown in **Figure 1**, five further articles were manually added, and full details of all 180 articles are given in the supplementary data.

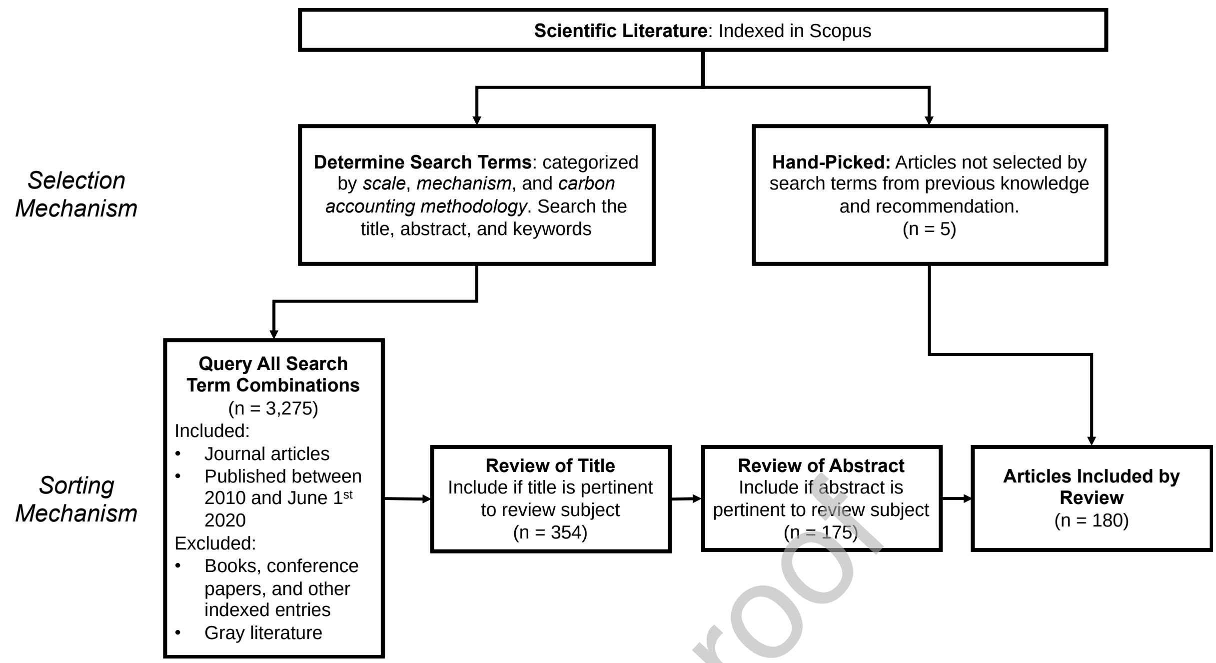

Figure 1. Overview of review methodology and bibliometric analysis.

Table 1. Search subterms used to search Scopus indexed journal articles. Subterms are grouped into three categories, the scale at which carbon storage is investigated, the mechanism for the carbon storage, and the accounting methodology used.

Scales	Mechanism	Accounting
construction material	carbon storage	life cycle
building material	carbon dioxide storage	climate credit
bio based construction material	carbon uptake	GHG
bio based building material	carbon dioxide uptake	greenhouse gas
renewable construction material	carbon sequestration	carbon emission
renewable building material	carbon dioxide sequestration	avoided emissions
biogenic construction material	carbon sink	carbon mitigation
biogenic building material	carbon dioxide sink	climate mitigation
wood	carbon capture	global warming potential
timber	biogenic carbon	embodied carbon
urban	bio-based carbon	carbon stock
building stock		carbon pool
built environment		carbon footprint

3.0 Carbon Uptake Mechanisms and Boundaries

3.1 Carbon Storage vs. Carbon Sequestration

The terms carbon storage, and carbon sequestration or uptake have been used interchangeably when discussing construction materials, yet each term has a different meaning. Carbon sequestration, or uptake, refers to the active process of removing carbon, in the form of carbon dioxide, from the atmosphere into a construction material. On the other hand, carbon storage refers to the construction material keeping the carbon as part of itself for a period of time. Recently, buildings and cities have been referred to as "carbon sinks" by both practitioners and academics, yet this term is often applied rather loosely when considering bio-based construction. A carbon sink is more generally understood as a pool that is actively removing carbon from the atmosphere, which in this context is the forest or crop, not the building. For clarity, we refer herein to buildings and cities as carbon storing, except in the case of carbon sequestration and storage of cementitious materials.

3.2 Carbon Sequestration Mechanisms

Two carbon sequestration mechanisms are identified when classifying carbon storing construction materials: plant photosynthesis and cementitious carbonation. Photosynthesis is the carbon sequestration mechanism associated with bio-based materials, such as harvested wood products (HWP), which convert carbon dioxide into biomass during the growth of the plant before being processed into a building material. This process is well described from a biological perspective. The second carbon sequestration mechanism is carbonation. Carbonation describes the process of carbon uptake in cementitious materials in which atmospheric carbon dioxide reacts with hydration products to form calcium carbonate (Ashraf, 2016). The carbonation of cementitious materials is well-studied from a durability perspective, and more recently has been considered when performing life cycle assessments of construction materials, assemblies, and buildings (Galan et al., 2010; Lippiatt et al., 2020; Souto-Martinez et al., 2018). The time at which carbon is sequestered depends upon the material. **Figure 2** shows during which lifecycle stage carbon is sequestered, in addition to illustrating the chemical details the two carbon sequestration mechanisms.

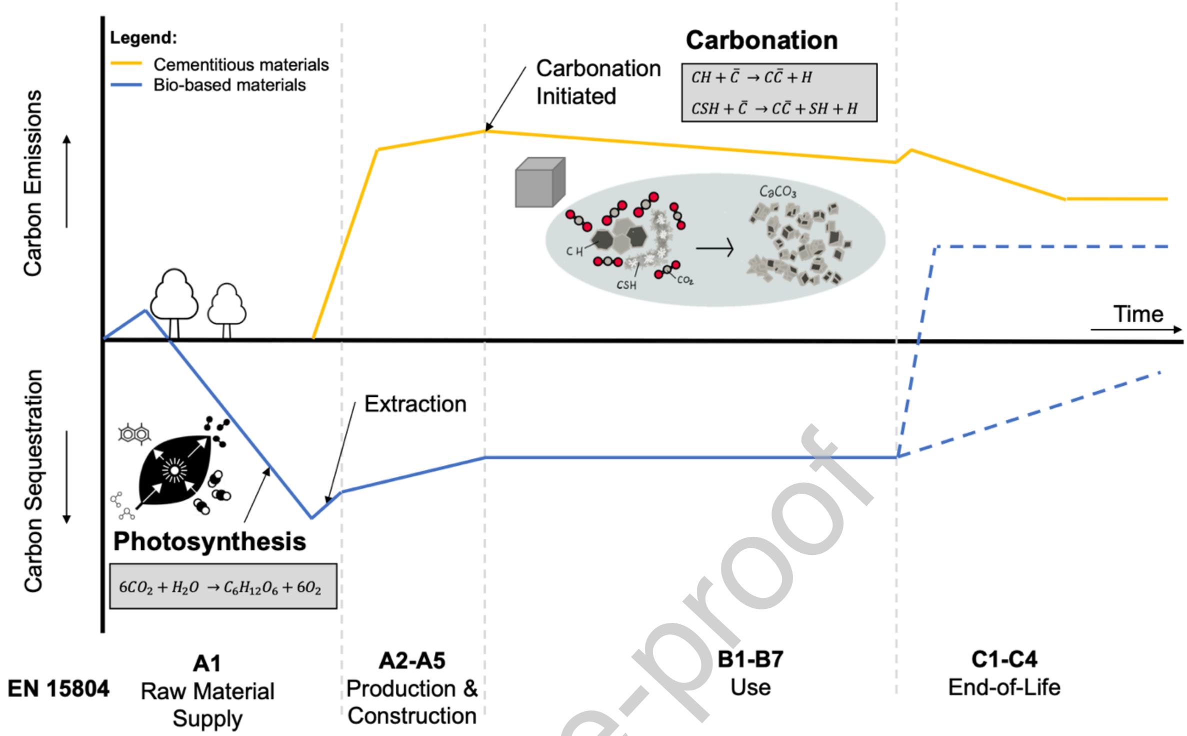

Figure 2. Carbon sequestration of cementitious and bio-based materials across different EN 15804 lifecycle stages. Photosynthesis occurs during the raw material supply phase (A1), while carbonation (as shown through oxide notation) is initiated after construction and continues through the end-of-life. The negative slope associated with carbon sequestration and subsequent storage translates to a "negative" global warming in many studies considered herein. Dashed lines for bio-based materials at the end-of-life stage cover possibilities at each end of the spectrum from instant oxidation in energy recovery processes, to long-term temporary storage in re-use, recycling, or landfill scenarios.. Note that the axes are not to scale. and that the time dimension should be interpreted loosely, as it can be argued that the growth of replacement trees planted after harvest is key to sequestration.

3.3. System Boundaries

Construction products at the end of their lifetimes are likely to release their temporarily stored carbon back into the atmosphere either in full (*e.g.* if incinerated) or in part (*e.g.*, if landfilled, or even if recycled as some losses are inevitable) (Hart and Pomponi, 2020). Therefore, for a complete picture of the climate change effects of biogenic carbon storage it is essential to consider the whole life of the product. **Figure 3** illustrates the stated or implied system boundaries of the 48 life cycle assessment (LCA) studies considered in this review, using the EN15804 terminology. 19 of the 48 studies do not cover any end-of-life stages, sometimes citing absence of quality data: most such studies follow convention and exclude biogenic carbon from their assessments. Exceptions, however, quantify biogenic carbon as a negative emission thereby implying permanent carbon storage and in some cases resulting in products with "negative" global warming, (*e.g.*, (Arrigoni et al., 2017; Florentin et al., 2017; Sinka et al., 2018)), although such results are often presented alongside analysis excluding biogenic carbon (*e.g.*, (Sierra-Pérez et al., 2016; Sodagar et al., 2011)).

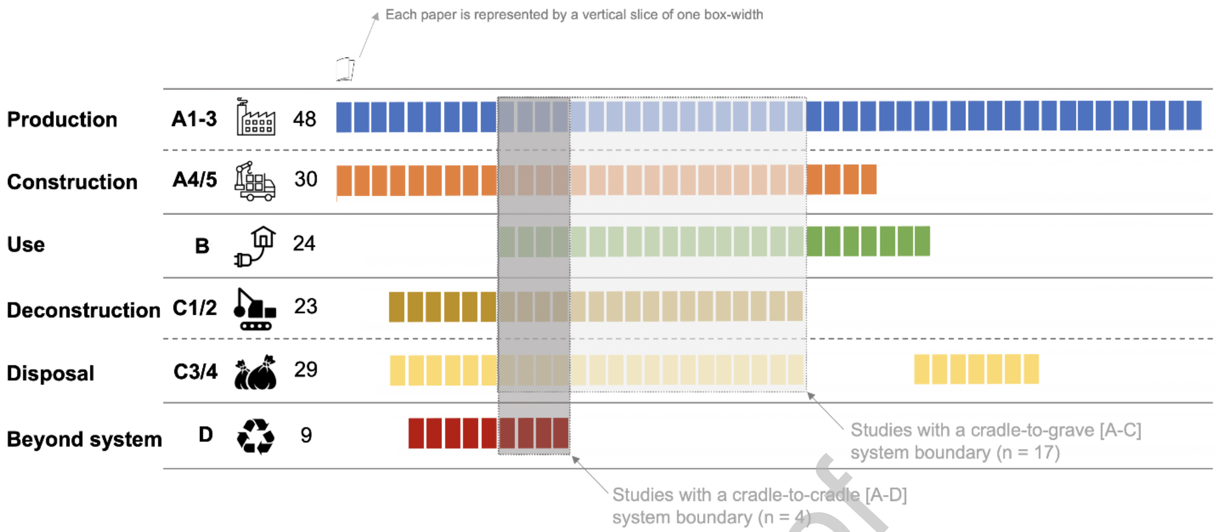

Figure 3. Distribution of life cycle stages considered by the 48 LCA studies captured in the present review. Note that in many cases this information is inferred, as the description of the system boundary is sometimes vague and with open-to-interpretation uses of terms such as 'cradle-to-gate'. It is interesting to note that despite the ever-growing literature on life-cycle assessment and circular economy only very few studies adopt an actual whole-life system boundary. A1-3: raw material supply and manufacture; A4/5: one or both of transport to site / construction; B: At least one module from stage B; C1/2: one or both of demolition / transport to waste processing; C3/4: one or both of waste processing / disposal.

Like-for-like comparisons between studies continue to be problematic, because of differing approaches to biogenic carbon and system boundaries. An LCA of particleboard by Garcia & Freire (2014), for instance, illustrates how the choice of assessment methodology affects the result: for a cradle-to-grave assessment ending in incineration, emissions ranged from 107 to 201 $kgCO_2e/m^3$ depending on whether the methodology used conformed with ISO/TS 14067, the GHG Product Protocol Standard, PAS2050 or the Climate Declaration guided the methodology. The range was even wider for the landfill scenario (including positive and negative values), depending on whether the assessment methodology deems a proportion of the biogenic carbon in landfill to be stored.

4.0 Carbon Accounting Methods

When discussing carbon storage in buildings, how carbon is accounted for shapes the conclusions that can be made. Broadly, there are three different groups of methodologies that have been used to account for carbon storage in buildings, (1) material flow analysis in units of $kgCO_2$ or kgC, (2) static life cycle assessment in units of global warming (GW)[1] under a particular time horizon, and (3) dynamic life cycle assessment in units of global warming impact. These methods differ in the ways in

[1] Much of the reviewed literature uses GWP (global warming potential) to refer to the life cycle impact category of global warming. In many cases we have interpreted the term GWP to GW, as GWP specifically refers to characterization factors for this LCA impact category, such as those published by the IPCC.

which biogenic carbon is treated and in which environmental accounting metric is used (Breton et al., 2018; Hoxha et al., 2020). A summary of which accounting methods were used most often in the reviewed papers is described by **Table 2**. Studies which used multiple accounting methods are counted multiple times, while methodological papers are excluded from the table.

Table 2. Distribution of methods used by the literature reviewed. Note papers that use multiple accounting methods (*e.g.*, comparing methods) are counted multiple times. HWP: harvested wood products.

Accounting Method		Number of Papers
Traditional LCA	Ignore biogenic carbon ('0/0' approach)	18
	Track biogenic carbon throughout ('-1/+1' approach)	15
	ILCD/PAS 2050	6
	Include biogenic carbon as a credit, ignore its end-of-life ('-1/0' approach)	16
	GWP100 (for non-biogenic carbon storage)	12
Dynamic LCA	Dynamic LCI	15
	GWP_{bio}	5
Other		8
Material Flow Analysis (carbon pools approach)	HWP carbon only	28
	Product/fuel substitution only	3
	Forest & HWP carbon	9
	Forest & HWP carbon & product/fuel substitution	14
	HWP & product/fuel substitution	8

Material flow analysis accounts for carbon on a per-mass basis, quantifying the amount of carbon which moves between carbon pools, such as live trees, dead trees, and removals from forests in the form of HWPs. This ecological accounting method is often coupled with the use of displacement factors (D_f) which include the reduction in emissions by the use of HWPs rather than other more carbon intensive construction materials. This methodology is the simplest and is used exhaustively in the reviewed papers.

Static life cycle assessment uses a midpoint indicator, global warming, to assess the warming impact of emissions of a system over a given time horizon. Common time horizons include 20, 50, 100, and

500 years. Static LCAs for buildings often report biogenic carbon separately, either ignoring it, since any carbon sequestered initially will be re-emitted ('0/0' approach), or including it as "negative emissions" in life cycle stage A and an equivalent positive emission in life cycle stage C ('-1/+1' approach). In some cases, the biogenic carbon is given a credit in the life cycle stage A, but the end-of-life scenarios (stage C) are ignored (referred to as '-1/0' approach). Other traditional methods include using GWP characterization factors or ILCD/PAS 2050 methods to account for carbon storage. While some traditional LCA methods attempt to capture the timing of emissions or sequestration, they often fail to account for how rotation periods affect biomass growth nor consider direct or indirect land-use changes (Hoxha et al., 2020).

In response, dynamic life cycle assessments use time-dependent life cycle inventories to account for the timing of emissions and provide a more rigorous treatment of biogenic carbon. Dynamic LCA is well described by Cherubini et al. (2012), Levasseur et al. (2012), and Levasseur et al. (2013), with the developed methodology utilised across many of the studies considered herein. Typically, biogenic carbon storage is considered temporary due to the temporal nature of bio-based construction materials, while storage by cementitious materials can be considered permanent.

With focus being paid to the ways in which buildings can store carbon, the need for dynamic life cycle inventories of HWPs has been realised. For instance, Head et al. (2020) developed gate-to-gate dynamic LCIs for Canadian HWPs. Likewise, a GWP_{bio} metric can be used to quantify the benefits of temporary carbon storage based upon forest dynamics, duration of storage, and end-of-life assumptions, and can be included alongside results from static LCA (Guest et al., 2013; Pingoud et al., 2012). Yet, Vogtländer et al. (2014) argue the point that the benefits of the temporary storage of biogenic carbon (for instance, measured as GWP_{bio}) can only be considered when there is both growth in forest area in addition to growth of HWP use that displaces other materials. The impact of temporary carbon storage extends beyond just carbon accounting, with the choice of methodology having an impact on the economics of carbon trading schemes (Marland et al., 2010).

The choice of accounting method is important, because it can lead to different conclusions. For instance, a glulam beam considered with a static LCA produces more favourable results than with a dynamic approach, especially under shorter time horizons (Cardellini et al., 2018). Similarly, for a cubic meter of structural timber, the choice of static or dynamic methods, amongst others, resulted in different conclusions surrounding net carbon storage, or net carbon emissions (De Rosa et al., 2018). When considering a whole building life cycle assessment, the methodology has significant impacts, similar to single products. For instance, a result of ~1,000 kg CO_2e/m^2 can be twisted to range between -300 to 1750 kg CO_2e/m^2 depending upon the choice of methodology (Røyne et al., 2016). Likewise, Penaloza et al. (2016, 2019), Knauf et al. (2015) and Guest and Strøman (2014) demonstrate how both methodological assumptions, choice of time horizon, and the carbon pools considered have an impact upon results of LCAs when considering biogenic carbon, finding that longer time horizons are more appropriate for considering the impacts of biogenic carbon storage. Since dynamic accounting methods rely on dynamic life cycle inventories, the end-of-life assumptions play a large role in evaluating a product, with recycling ranking better than other potential end-of-life scenarios (Morris, 2017). Tellnes et al. (2014) uses a time-adjusted biogenic GWP to investigate the carbon footprint and carbon storage potential of selected wooden façade materials. Their time-adjusted results show that these methods have a potentially large effect on the carbon footprint of wooden cladding; in fact, carbon flows and timings of emissions appear more significant than the difference between the wooden products (Tellnes et al., 2014). These results confirm earlier works wholly dedicated to uncovering these aspects of LCA of biogenic and other carbon-storing materials (Levasseur et al., 2013).

5.0 Carbon Storage Potential of materials

In this section we review papers that report on or quantify carbon storage in biogenic materials (primarily wood, but also crops and crop residues), and cementitious materials, which sequester carbon during and after the use stage.

5.1 Harvested Wood Products

The scope for durable HWP, especially construction products deeply embedded in long-life buildings, to mitigate climate change by storing carbon over long time periods has interested researchers approaching the topic from a variety of perspectives. These include biogenic carbon in LCA, cascading strategies to extend the life of HWP, and the global and regional potentials for HWP carbon storage, in some cases linking this to carbon storage in the forest. The underpinning idea is that wood is approximately 50% carbon by dry mass, and that a growing anthroposphere (primarily buildings and landfill sites) might add to stocks of carbon in stored HWP at a higher rate than stocks are removed through oxidation processes. Although this may result in carbon losses from the forest carbon pool (partially compensated by regrowth), in some circumstances the net effect might be an overall increase in carbon stored in the combined forest-HWP system.

5.1.1 Substitution benefits

Analyses of carbon pools are typically founded on quantification of carbon flux and storage in a system comprising forest, buildings or HWP more broadly, and solid waste disposal sites (SWDS, or landfill), but they are frequently extended to include an ever-increasing ‘virtual’ pool of substitution benefits. **Figure 4** visualises these carbon pools. Material substitution benefits are the life cycle GHG emissions avoided by choosing HWP rather than, say, concrete or steel. They are often expressed as a substitution factor (S_f), usually defined as GHG emissions avoided by substituting the default option divided by the GHG emissions of the default, or a displacement factor (D_f), which is the GHG emissions avoided in terms of kgC divided by the mass of carbon in the wood product. Care is needed in interpretation, as in at least one article (Hildebrandt et al., 2017), substitution benefits are referred to as carbon storage without explicitly stating that this virtual pool of carbon is what is being discussed, not the carbon physically embedded in the wooden buildings. Energy substitution in this context is the substitution of fossil fuels through the combustion of end-of-life wood, or landfill gas: sawmill residues used as fuel within the supply chain of the HWP (e.g. for drying sawnwood) contribute to the material substitution pool.

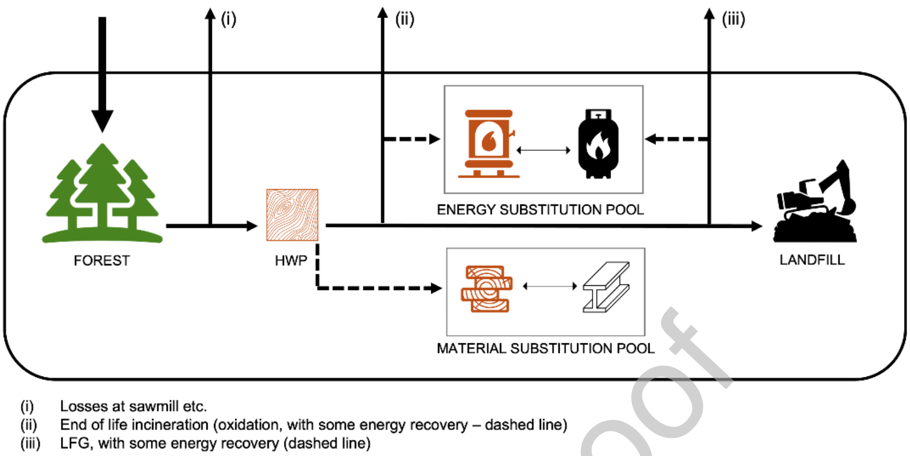

Figure 4. The carbon pool system of forest, HWP, landfill and substitution pools. The solid lines indicate the physical flux of carbon from the atmosphere (photosynthesis), between pools, and back to the atmosphere. The dashed lines represent the contribution of the relevant processes (e.g. use of HWP instead of concrete, or landfill gas – LFG - energy utilisation) to the 'virtual' substitution pools.

Some authors argue that the substitution benefits are permanent, in contrast to the physical carbon pool, which is destined for eventual release back into the environment, with 86% of sequestered carbon lost within a century according to Ingerson (2011). However, Harmon (2019) argues that substitution benefits do not provide the promised ever-increasing climate change mitigation contribution, and certainly not when projected decades into the future; furthermore, the process of 'leakage' means any gains are not permanent. There are many facets to this discussion, but one simple point is that as energy networks and industry continue to decarbonise, the real displacement and substitution factors will decrease: this is already occurring in many regions, but models tend to assume constant displacement or substitution factors: this overestimates the substitution benefits. Peñaloza et al. (2018) and Kalt (2018) are examples of research that do account for this.

In their much-referenced meta-analysis of displacement factors, Sathre and O'Connor (2010) find an average D_f of 2.1 kgC/kgC, with most of the 21 studies coming between 1.0 and 3.0; and Geng et al. (2017) find a D_f range from 0.25 to 5.6 in studies dating between 1993 and 2016, but the upper figure is an outlier and its derivation from the source material is opaque. Nepal et al. (2016) apply a D_f of 1.68 to the analysis of scaling up of non-residential construction in the USA: when the boundary is extended to include changes in the forest and HWP carbon, the average D_f increases to 2.03. It is worth noting that much of the source material for D_f values is decades old: as manufacturing gradually decouples from GHG emissions, D_f values should decrease over time, and a more recent study (Smyth et al., 2017) does indeed report a D_f of 0.54 for sawnwood, and 0.45 for panels. Some LCA studies include sufficient information to permit the estimation of both D_f and S_f by the reader. For instance Crafford et al. (2017) compare timber and steel truss roofing systems: in one example, the cradle-to-grave emissions for the timber truss is 85 $kgCO_2e$ compared to 1038 $kgCO_2e$ for a steel comparator: it follows that $S_f = 0.92$. The timber truss stores approximately 274 kg of carbon (1004 $kgCO_2e$), so $D_f = 0.95$. In this case S_f and D_f are very close to each other, but there is no reason to expect this in general.

An alternative to using off-the-shelf displacement factors is to invert the viewpoint and investigate the D_f required to achieve certain goals. In their scenario analysis of carbon pools related to $1m^3$ of harvested wood, Butarbutar et al. (2016) note that a D_f as high as 2.9 is required to offset the overall emissions when natural gas is the energy source for the material substituted. Seppälä et al. (2019) find that to justify a 33% increased harvest of timber in Finland, a D_f of 2.4 is needed. However, they report that the real average D_f is likely to be below 1.1, which presents a serious challenge to increased harvesting in Finland.

Chen et al. (2018a) assumes a generous displacement factor of 2.43 to underpin their more optimistic conclusions about the benefits of increased harvest in Canada. They argue that better targeting of forest products towards long-lived HWP allows the carbon debt of increased harvest rates in the Ontario province to be repaid within 20 years, and – at the end of the simulation in 2100 – an extra 187.9 MtC of carbon pooled. For Canada overall, Chen et al. (2018b) find that it will take from zero to 84 years to repay the carbon pool losses from harvest (84 years is business as usual, zero years when there is a dramatic shift towards structural panel manufacture as these have the best D_f). A sensitivity analysis using a low-end estimate of 0.68 tC/tC for D_f resulted in the minimum time to carbon sequestration parity for structural panels being 75 years, not zero.

Werner et al., (2010) consider the forest, HWP and substitution pools under different scenarios in Switzerland, concluding that use of wood in long-lived construction products is the best approach for climate change mitigation. Braun et al., (2016) calculate a climate change mitigation efficiency (CCME) metric for timber use in Austria, in the range of 0.61 to 0.68 tCO_2e/m^3 of wood used (averages between 2025 and 2100), depending upon the scenario. Physical and virtual carbon pools are considered here, but energy substitution is the dominant force, as wood is calculated to substitute a mix of fossil fuels throughout the period of the study.

5.1.2 HWP Carbon – National Accounting

The IPCC has issued guidance and subsequent revisions on the reporting of carbon fluxes in forestry and HWP in national accounts (Hiraishi et al., 2013; Pingoud et al., 2006), which has resulted in extensive literature comparing approaches and results. Of the three approaches detailed in the IPCC guidance (IPCC 2006), only the stock change approach can accurately reflect changes in stocks of all HWP in a given country or region, irrespective of the location of the forest, and is therefore the most relevant to this review's focus on the built environment. In the production approach (prescribed for national reporting by the IPCC 2013 guidance, and therefore the approach adopted by much subsequent literature) imported HWP is not considered: the focus is on storage of domestically-grown timber, whether consumed domestically or exported. The system boundaries are shown in **Figure 5,** adapted from IPCC (2006).

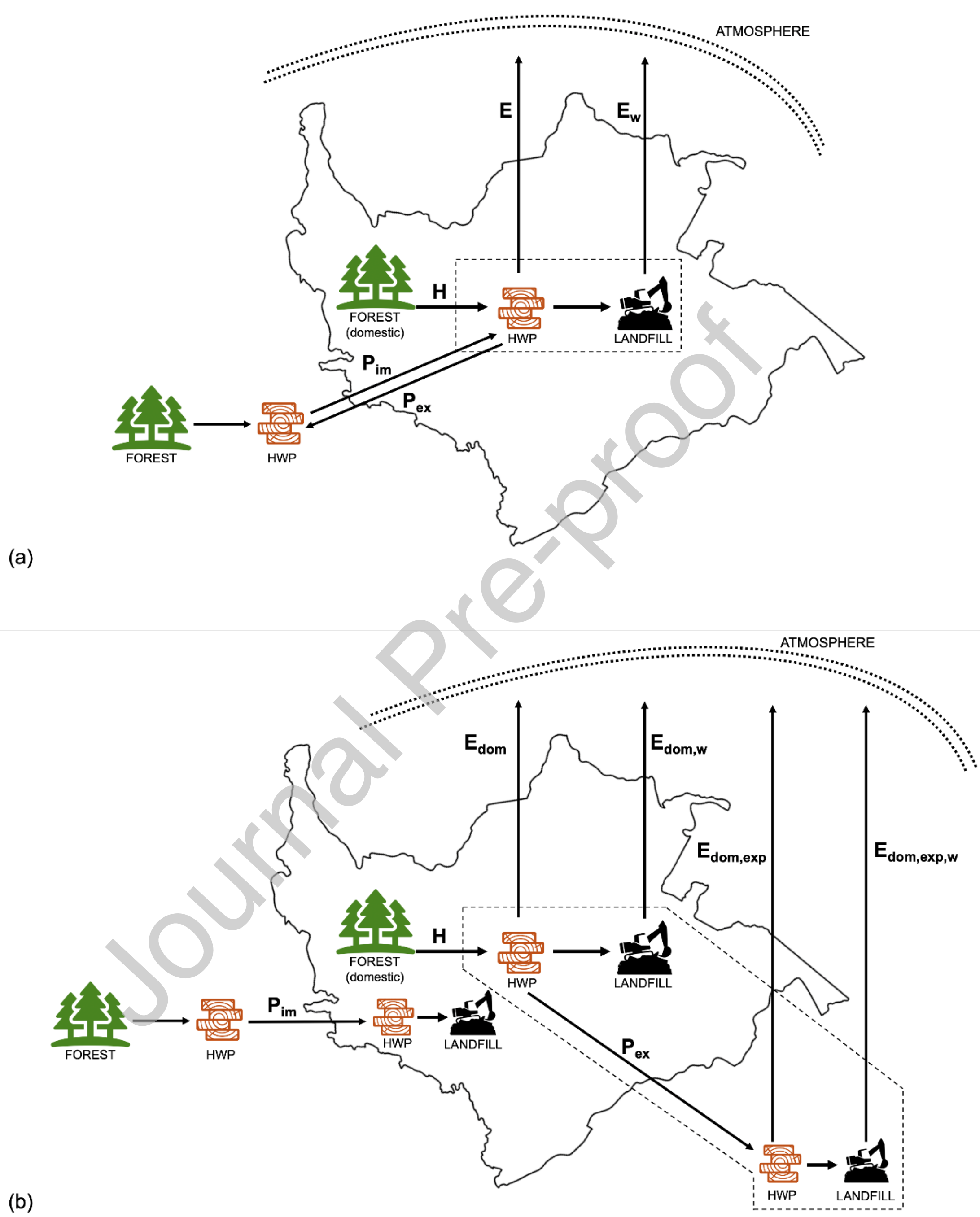

Figure 5. HWP accounting approaches. The irregular shape represents a geographical boundary, the dotted line is the HWP accounting system boundary. Quantities representing carbon transfers are H: domestic HWP production; P_{im}: imports; P_{ex}: exports; E: carbon loss from HWP to the atmosphere; the subscript $_w$ relates to HWP in SWDS/landfill; the subscript $_{dom}$ relates to domestically produced HWP, and $_{exp}$ to exported HWP. (a) Stock change approach. Net emissions from HWP = - (H + P_{im} – P_{ex} – E – E_w), and

the contribution to HWP stock is the same number with opposite sign. (b) Production approach. This tracks domestically produced HWP, at home and abroad. Net emissions from HWP = - (H – E_{dom} – $E_{dom,w}$ – $E_{dom,exp}$ – $E_{dom,exp,w}$).

Although HWP stocks include the less durable paper and paperboard category, the transient nature of these products limits their contribution to the HWP stock, and it is reasonable to expect a significant proportion of HWP being attributable to long-lived products and construction. For this reason, articles including all HWP are included in **Table 3**. In the case of China, for instance, Zhang et al. (2019) report that 76% of the carbon stocks are in wood-based panels and sawnwood, 10% are in SWDS, with the remaining 13% in short-lived products such as paper. Information that could in theory be used to segment the long-lived products category is provided by Churkina et al. (2010) and Negro and Bergman (2019), who provide metrics for carbon stored in furniture in per capita or per floor space metrics.

Table 3 shows the net and cumulative carbon stored in HWP for the given geographical area as defined by the stock change approach, although the approach used is immaterial in the case of global figures, as there are no reliable reports of interplanetary trade in HWP. On a per capita basis, the annual net increase in HWP carbon varies from negligible (Japan in recent years) to more than 50 kg, and the cumulative HWP storage is typically equivalent to almost (sometimes exceeding) one year of energy-related GHG emissions.

Table 3. Annual and cumulative carbon stored in HWP (just the durable categories of HWP when the information is available excluding paper and paperboard) in various regions and times. Annual figures (including averages over short time periods) in the left block, and cumulative figures covering substantial time periods to the right. Qualification for inclusion: national or supranational data reporting net results; reported numerically rather than graphically; stock change approach stated or implied. Forest carbon is not considered. *particleboard/fibreboard industry alone. Population data and projections as far as 2050 from worldometers.info (2020) and national CO_2 emissions are from energy consumption, (IEA, 2020).

	REGION	ANNUAL CARBON STORAGE IN HWP				CUMULATIVE CARBON STORAGE IN HWP				Scope	Reference
		Year	MtC yr^{-1}	tC yr^{-1} cap^{-1}	Share of annual CO_2 emissions	Period	MtC	tC cap^{-1}	Share of annual CO_2 emissions		
	Global	2008	80	0.0118	1.0%	to 2008	7000	1.03	86%	All HWP	(Lauk et al., 2012)
	Global	2015	335	0.0454	3.8%					All HWP	(Johnston and Radeloff, 2019)
	Global	2030	441	0.0516	4.3%					All HWP	(Johnston and Radeloff, 2019)
	UK	2005	1.6	0.0265	1.8%					Long-lived products	(Robson et al., 2014)
	Spain*	2006	1.0	0.0215	1.5%					Long-lived products	(Canals-Revilla et al., 2014)
	Slovakia	2017	0.303	0.0556	3.5%					Long-lived products	(Parobek et al., 2019)
	China					1961-2011	530	0.39	21%	Long-lived products	(Ji et al., 2013)
	Indonesia					1961-2016	72	0.28	50%	All HWP	(Aryapratama and Pauliuk, 2019)
	Japan	2013-18 average	0.085	0.0007	0.0%					All HWP	(Tsunetsugu and Tonosaki, 2010)
	Japan					to 2004	280	2.18	93%	All HWP	(Kayo et al., 2014)

REGION		ANNUAL CARBON STORAGE IN HWP				CUMULATIVE CARBON STORAGE IN HWP				Scope	Reference
		Year	MtC yr^{-1}	tC yr^{-1} cap^{-1}	Share of annual CO_2 emissions	Period	MtC	tC cap^{-1}	Share of annual CO_2 emissions		
	Japan					to 2050	254 - 312	2.40 - 2.95	102-126%	All HWP	(Kayo et al., 2014)
	Taiwan	1990-2008 average	0.87	0.0378	1.4%					All HWP	(Lee et al., 2011)
	Brazil					1900-2016	252	1.22	236%	All HWP	(Sanquetta et al., 2019)

The distillation of future scenarios down to a number of course conceals many important insights. For instance, Kayo et al., (2015, 2014) noted that wood promotion is required to prevent HWP carbon stocks in Japan from declining on account of decreasing HWP volume availability, although there is a possibility of increasing carbon storage in roundwood products in 2050 by 262% (2013 baseline), mostly in buildings. Pilli et al., (2015) projected a decrease in carbon storage in the EU by 2030 under a 'constant harvest scenario', but storage can be kept at approximately the historical level by following an increased harvest scenario. This illustrates how HWP stocks can start to saturate over a relatively short period without aggressive HWP promotion initiatives.

5.1.3 HWP carbon plus forest carbon

In this section we summarise results from articles that look at stored carbon in the HWP-forest system, by region.

A Canadian study (Chen et al., 2014) is a reminder that past performance is not necessarily a guide to the future. In the 110-year study period to 2010, 7510 MtC (net) was stored in Canadian forests, with an additional 849 MtC accumulating in HWP. However, the increase in forest carbon is related to disturbance in the 19th Century and will not be repeated in the current period, therefore future opportunities are said to be in substitution benefits, so using timber more wisely should be emphasised, rather than using more timber. Focusing on Washington State, Ganguly et al., (2020) report an overall carbon sink both for forests (7.4 $MtCO_2e$/yr) and for the wood products obtained from them (4.3 $MtCO_2e$/yr), a combination sufficient to mitigate 12% of the State's GHG emissions. By contrast, Nunnery and Keeton (2010) find that the best scenario for stocks of carbon in forests and HWP in the USA is no harvest. Thus, any intervention leads to a decline in overall stored carbon, with clear-cut harvest providing the worst outcome, with an average stock reduction of 85 tC/ha over the 160-year simulation period. Viewed from an alternative perspective, shifting from a clear-cut management system to individual tree selection increases carbon stocks by 41 tC/ha.

Moving to Scandinavia, Soimakallio et al. (2016) found that carbon sequestration in the forest exceeded the direct emissions from timber use and fossil fuel use in its processing, by 3.6MtC. However, if the comparison is made with a reference system in which no harvesting takes place, then life cycle emissions averaging 15.1 MtC/yr are calculated. They conclude that it is unlikely that increased wood utilisation can contribute to significant emissions reduction target due to the net loss of carbon sink in the forest. In their retrospective analysis of data from HWP and forests in Finland, Sweden and Norway, 1960-2015 Iordan et al. (2018), calculate that the three countries transition from current sources to sinks between 2000 and 2014, but on a cumulative basis it takes until 2020 to 2045 to enter carbon negative territory.

In contrast to the many studies on intensive management in boreal and temperate forests, Alice-Guier et al. (2020) studied the carbon balance of selective logging in Costa Rica. They found that 0.443 tC per hectare of forest per 15-year cycle was stored in the resulting construction products.

Whilst the total harvest is significantly larger, forest growth appears to exceed extraction overall as a result of growth rates increasing after thinning.

5.2 Cementitious Materials

Cementitious materials, including concretes and mortars, have been shown to sequester non-negligible quantities of carbon at a variety of scales. Two primary models (Lagerblad, 2006; Souto-Martinez et al., 2017) exist for quantifying the carbon sequestration potential. Both are rooted in the stoichiometry of hydration reactions and consider the carbonation of calcium hydroxide and/or calcium silica hydrate. The models differ in how they consider pozzolanic materials. These models have been used at scales, ranging from the single building element (*e.g.,* a column) to the global, to quantify how much carbon can be sequestered and ultimately stored by cementitious materials. Similarly, the carbonation model has been applied to other cementitious material systems, such as pervious concrete (Ellingboe et al., 2019). Souto-Martinez et al. (2018) showed that depending upon the type of cement and cross-sectional geometry, a reinforced concrete column could sequester up to 19% of the initial emissions released. Similarly, 18-21% of initial emissions could be sequestered by a reinforced concrete structure which accounted for recycling at the end-of-life (Andersson et al., 2013). Using recycled concrete, when accounting for second generation carbonation, can offset 55-65% of total emissions for a structure (Collins, 2013). Utilising waste CO_2 to form stable carbonate-based construction materials is another way in which carbon is stored by cementitious materials. For example, carbonated blocks can offer substantially lower embodied carbon coefficients compared to ordinary portland cement-based blocks (Di Maria et al., 2020). Lime is another cementitious material that, while carbon-intensive in manufacturing, has the potential to store carbon through an aerial carbonation process, especially when coupled with a low-mileage supply chain (Forster et al., 2020).

When considering carbon sequestration of cementitious materials at the building stock scale, various estimates have been made. The carbon sequestration capacity of the Spanish cement stock was estimated to be 146,902 tonnes of CO_2 per year (Andrade and Sanjuán, 2018). At the global scale, existing concrete and mortar stocks are responsible for annual sequestration rate in 2013 of 0.915 $GtCO_2$, and between 1930 and 2013 were estimated to sequester 16.5 $GtCO_2$ (Xi et al., 2016). Looking to the future, uptake from cementitious materials is significant, with an estimated 30% of emissions between 2015 and 2100 potentially being reabsorbed (Cao et al., 2020). The field of concrete carbonation is extensive, and those studies considered herein were included based upon the systematic search criterion. For an extensive review of concrete carbonation, the reader is referred to Ashraf (2016).

At a completely different scale, Lee and Wang (2016) assessed the carbon uptake of slag-blended concrete structures through carbonation and showed that a 44,000 square meter building can store 113,000 kg CO_2 after 50 years of service. The floor space normalised value (2.56 kg CO_2/m^2) appears significant and worthy of further investigation.

5.3 Hempcrete

Hempcrete, or hemp-lime composites, is a composite insulation material composed of hemp shiv and a lime-based binder. Hempcrete is commonly referred to as a carbon-storing material due to it sequestering carbon, through both photosynthesis and carbonation mechanisms, over its life cycle (Ingrao et al., 2015). During the cultivation of hemp, sequestration occurs through photosynthesis, but emissions are also associated with the growing, harvesting, processing, and transportation. These cradle-to-gate emissions range between 0.104 and 0.975 kg CO_2e/kg without including biogenic carbon, and -1.74 and -0.315 kg CO_2e/kg when biogenic carbon is included (Scrucca et al., 2020; Zampori et al., 2013). The large range between these figures is a result of the allocation methodology chosen for each LCA.

In addition to large variation in the emissions associated with hemp cultivation, an even larger range of carbon sequestration metrics is arrived at when considering hempcrete assemblies. This result is due to the choice of binder (*e.g.*, hydraulic or pozzolanic), the density of the mix design (*i.e.*, quantity of binder), and the model used for quantifying sequestration due to carbonation. Three primary models for hempcrete carbonation exist, and range in the complexity to which they consider the hydration reactions of both hydraulic or pozzolanic binders (Arehart et al., 2020).

The comparison of the carbon storage potential of hempcrete between studies is difficult due to the choice of functional unit. As a thermal insulation material, the thermal conductivity greatly influences the thickness of hempcrete required to achieve a particular U-value. For instance, for a 1m^2 wall, the total greenhouse gas balance ranges from -1.6 kg CO_2e/m^2 (Pretot et al., 2014) to -26.01 kg CO_2e/m^2 (Arrigoni et al., 2017) depending upon the wall type, construction method, and U-value achieved. There is no standard functional used between LCAs of hempcrete and would benefit from the definition of a product category rule.

While hempcrete traditionally utilises a lime-based binder supplemented with a hydraulic binder to accelerate the set-time, alternative binder materials and coatings have been proposed. For instance, magnesium-based binders that replaced lime-based binders significantly reduced initial emissions, which while decreasing the magnitude of sequestration through carbonation, makes the greenhouse gas balance more favourable to net-storage (Sinka et al., 2018). Additionally, the lifespan of hempcrete can be increased through the use of a sol-gel coating. Yet, the inclusion of this coating resulted in additional environmental impacts, negating any benefit achieved through carbon storage (Heidari et al., 2019). While hempcrete has historically been used in Western Europe, it has also been shown to be an effective insulation material for residential construction in arid climates (Florentin et al., 2017). Hempcrete, while having a long history of use, is again emerging as a thermal insulation material that has the potential to sequester and store (both temporarily and permanently) more carbon than it emits, depending upon its mix design.

5.4 Other Materials

There are a myriad of other alternative construction materials, both cementitious and bio-based which store carbon This section aims to capture other construction materials, based on well-developed, market-ready technologies, which sequester and store carbon.

Straw is a fast-growing material that sequesters carbon through photosynthesis, typically on an annual cycle. Straw can be baled together to form exterior walls, and is a construction technique recently revitalised due to its potential for carbon storage and low embodied emissions as compared to other detached residential construction (Lawrence, 2015; Sodagar et al., 2011). In addition to being used as a construction material, straw can also be used as biochar to improve soil carbon sequestration, with Mattila et al. (2012) finding that producing straw bales resulted in more carbon storage than biochar (3.3 t CO_2e vs. 0.9 t CO_2e), illustrating how certain construction materials can contribute to a carbon sink if adopted widely.

Bamboo is another bio-based material which has potential to replace carbon-intensive construction materials, especially in the Global South. For example, in Colombia, bamboo construction has the potential to reduce the embodied carbon intensity of residential buildings from 155 kg CO_2e/m^2 to -5 kg CO_2e/m^2 (Zea Escamilla et al., 2018). By utilising bamboo rather than brick or concrete hollow block construction, the buildings shifted from having net carbon emissions, to net carbon storage. In addition to being used as a structural material, bamboo can be used as a flooring material, with Gu et al. (2019) showing net carbon storage of -14.89 kg CO_2e/m^3 when including biogenic carbon.

Cork has been used as a renewable thermal insulation material, reducing both operational and embodied impacts of buildings, primarily due to it being bio-based. Silvestre et al. (2016) shows through a traditional LCA that the carbon storage potential of cork is 435 kg CO_2/m^3 of insulation (density of 110 kg/m^3) in comparison to total embodied emission of 38.3-47.1 kg CO_2e/m^3 . Likewise, the manufacturing process for cork insulation has a significant impact on the total life cycle emissions (Sierra-Pérez et al., 2016). For expanded cork slab and granules which have more intensive manufacturing processes, carbon storage during use and end-of-life between 77.1 and 128.4 kg CO_2e/m^3 was calculated, depending upon the assumed lifespan of the material (30 or 50 years respectively) (Demertzi et al., 2017).

While many of the advances in material sciences have focused on development of plant-based materials for construction, other novel materials are under development. For instance, mycelium is a living, fungal material which can be used as a thermal insulation material. These bio-based, living materials show promise to contribute to increasing the carbon stored within buildings (Violano, 2018). In addition to virgin materials, biomass wastes are increasing at the global scale due to population growth and have the potential to become feedstocks for high-volume construction products (Tripathi et al., 2019). When considering waste materials, further carbon storage by construction materials can be achieved, by avoiding the demand for virgin feedstocks.

Lastly, Salzer et al. (2017) carried out an LCA of conventional and alternative construction methods for social housing in emerging economies (the Philippines), and reported for an assessment of the stages A–B–C–D with GW, a 35% reduction for soil–cement blocks, 74% for cement–bamboo frame, and 83% for coconut board-based houses compared to a reference house made of concrete.

6.0 Buildings Scale

In this section we review papers with an interest in the carbon storage of building assemblies (structure and envelope), whole buildings, and building stock.

6.1 Structural System

The life cycle climate impacts – including carbon storage – of building elements such as the structural system are often accounted for by LCA studies set out to look at buildings as a whole. Nonetheless, some studies analysing the specific contribution of structural systems and/or components in isolation can also be found in literature.

Many of these studies are comparative in nature, and consistently favour biogenic materials without fully exploring the benefit of temporarily stored carbon, but with a range of substitution factors from 0.09 to 0.74. Nässén et al. (2012) for instance evaluated the GW of two functionally equivalent versions of four-storey building frames of timber and reinforced concrete. Their analysis spans over a time horizon of 100 years and conclude that the timber frame option would yield 50% lower emissions compared to the reinforced concrete counterpart if current energy supply systems remain unaltered by 2050 (*i.e.*, a substitution factor S_f of 0.5). Another LCA assesses and compares the GW of Cross Laminated Timber (CLT) and reinforced concrete floor slabs, controlling for span length and load bearing capacity, again finding the timber-based material to have a lower GW compared to the reinforced concrete counterpart (Hassan et al., 2019). According to this study, embodied carbon intensity ($kgCO_2e/m^2$) of CLT floor slabs compared to reinforced concrete slabs results in S_f of ~0.74. Similar conclusions are also reached by Malone et al. (2014). Bolin and Smith (2011) focus in on structural components such as borate-treated sawn lumber for structural perimeter wall framing, and found a GW reduction of 34% as compared to the steel frame baseline. Similarly, Crafford et al. (2017) and Wijnants (2019) also provide results that favour timber in the use of, respectively, roof and rooftop extension systems.

A more recent study by D'Amico et al. (2021) reports timber as a less carbon-intensive construction material regardless of its carbon-storage potential. By fully replacing, at the global scale, composite steel-concrete floors in steel building frames with CLT panels, between 20 and 80 Mt CO_2e would be avoided by 2050 (cradle-to-grave analysis of the building superstructure, excluding the biogenic carbon storage).

Several other building structure studies combine some form of LCA and MFA to build a picture of carbon storage and substitution effects at the building stock level, the results of which are summarised in Section 7.0. For instance, Zea Escamilla et al. (2016) evaluated the use of engineered bamboo in construction for residential housing programmes in the Philippines as alternative to concrete hollow block structural walls, providing a dynamic account of all carbon fluxes in the bamboo growth, processing, building construction and end-of-life over a period of 130 years. A methodological study by Hafner and Rueter (2017) estimating the effect of shifting from conventional building structures to timber-based ones at the national scale is applied to the domestic building stock of Germany. Their analysis shows that if the benefit of carbon storage is excluded, then the timber-based residential buildings would still result in S_f values in the range 0.09-0.56. Finally, Heräjärvi (2019) estimates the volume of biogenic carbon stored in wooden building structures every year for both Finland and globally from 2003 to 2019, and reports that about 90% of global lumber production would have to be used for construction of wooden buildings in order to biogenically store 1% of global anthropogenic emissions. Arguably this observation says as much about the increasingly urgent imperative to reduce global GHG emissions as it does about the impotence of carbon storage in buildings as a mitigation strategy for the built environment.

6.2 Building Envelope

Relatively few contributions were found within the domain of buildings' façades and envelopes. However, these studies do include some of the key contributions to the ongoing debate around the importance of a dynamic approach to LCA: one that considers the timing of emissions and how this impacts the resulting conclusions.

Specifically, Pittau et al. (2018) explored the opportunity offered by fast-growing bio-based materials as a carbon storage solution for external walls through a dynamic cradle-to-grave LCA study with a time horizon of 200 years. Out of the alternatives considered in the study, only straw and hemp wall constructions (not brick, concrete or – more interestingly - timber) are found to have a negative impact on radiative forcing (i.e. better than climate neutral) throughout – or indeed at any point during – the time frame considered. This is because the biomass harvested from the field is replaced within twelve months, in contrast to the timber option, where decades are needed to replace the harvested biomass. Partly from the same authors, a follow-up study extended the level of analysis to retrofitting the EU housing stock, to explore the resulting carbon storage potential (Pittau et al., 2019). This study also uses a dynamic LCA methodology over 200-year time horizon, with a functional unit of $1m^2$ of retrofitted wall wrapped around the same cradle-to-grave system boundary. Similar to their previous study, the authors investigated envelopes with straw, hempcrete, timber and standard insulations. Only straw- and hempcrete-based solutions achieve net carbon removal, and the study's estimates for removals by 2100 are 281 Mt CO_2e for the I-joist frame with pressed straw, 54 Mt CO_2e for the pre-assembled frame with injected hempcrete and 84 Mt CO_2e for the hempcrete blocks.

Two further LCA studies of wall elements that put timber options well ahead of the alternatives are Lupíšek et al. (2017) and Pomponi and D'Amico (2017). From a cradle-to-gate (A1-A3) perspective, the former study compared a wood-based curtain wall panel with an aluminium one, and the latter study compared a timber-based double skin façade and a traditional envelope solution assessed over its whole lifecycle including the operational stage B6 and module D as an option.

6.3 Whole Building and Other Assembly

Two studies in this category have adopted a dynamic LCA approach (Fouquet et al., 2015; Negishi et al., 2019). Fouquet et al. (2015) assessed a whole building with a floor area of 122 m^2 compliant with Passivhaus standards, covering the full life cycle (A1-5, B5-6, C1-4) with time horizons of 100, 150, and 500 years. Regardless of the time horizon the timber house outperforms the concrete alternative: 35% reduced impacts over the 100-year horizon, and 45% over the 150-year horizon. The different methods do not seem to change the ranking of the different house typologies but do change the relative difference between the results: the gap between the landfilled timber house and the concrete house vary from 40% to 60% with dynamic LCA (Fouquet et al., 2015). Negishi et al. (2019) also focus on an entire building from a life cycle perspective (A1-5, B1-2, B4, B6-7, C1-4). Their GWP time horizon is 100 years, but the analysis spans a period of 201 years: a past time horizon of 150 years to account for tree growth for the different tree species included in the background inventory and the calculation; then 50 years for the lifetime of the building (50 years) and one supplementary year for dismantling and waste management. The authors found a 71% improvement offered by wood products compared to concrete products in the GW impact category, but also concluded on the difficulty of comparing GWP100 results with a dynamic LCA given the major differences in the nature of their indicators (Negishi et al., 2019).

Several others focus on normalised units of floor area (*e.g.* 1m^2) for whole building case studies (Hafner and Schäfer, 2017; Nakano et al., 2020; Padilla-Rivera et al., 2018; Pierobon et al., 2019; Ximenes and Grant, 2013). These studies, and therefore their findings, are however difficult to compare mainly due to differences in the choices of functional units, different system boundaries, and different ways of reporting results. For instance, GHG reductions of 28 and 33 t CO_2e are seen for two house types in Sydney from a life cycle perspective as reported by Ximenes and Grant (2013), and 26.5% lower GW impact as well as 1,556 - 2,567 t CO_2e stored in the CLT components of the building in the cradle-to-site study from Pierobon et al. (2019). This miscellaneous collection of results in the LCAs of buildings is not new (Pomponi and Moncaster, 2016) but the fact that several of the studies above were published after the 2016 review by Pomponi and Moncaster (2016) suggests the black-box nature of many LCAs of buildings remains a challenge. These issues will hopefully reduce in both frequency and magnitude thanks to ongoing efforts to promote existing guidance as well as developing new ones. For instance, the mandatory Professional Statement by the UK's Royal Institution of Chartered Surveyors (RICS, 2017) has gained global traction and is informing building policy and urban planning in the UK and beyond. Similarly, the ongoing activities of the Annex 72 of the International Energy Agency (a global project due to be completed in a year's time) are producing harmonized methodological guidelines based on an extensive appraisal and thorough understanding of international practice (Frischknecht et al., 2019; Soust-Verdaguer et al., 2020). Given its global remit, the latter gives hope for a quick uptake of a unified methodology and harmonized methods for whole building LCAs which are transparent, consistent, replicable and therefore comparable.

7.0 Building Stock Scale

Several researchers have quantified the carbon physically stored in a defined building stock, from all buildings across the globe, down to buildings in a defined category and specific location. Key results are presented in **Table 4**, which include estimates of current stock, annual stock changes, and future scenarios.

At the building stock scale, research has typically taken an urban metabolism approach to quantifying both the carbon flows and carbon storage at the urban scale. Oftentimes, this stored carbon is not specific to just construction materials, but rather encompasses all carbon-based materials used. For instance, Chen et al. (2020) quantified the physical "urban carbon" that is stored across 16 cities. The total amount of carbon stored in 2008 across all cities ranged between 0.6 and 1.5 tC cap^{-1}. Note that these figures do not separate the carbon attributed specifically to construction materials. Similarly, Churkina et al. (2010) quantified the total carbon stored in US urban areas, finding that human settlements can store as much, if not more, carbon per unit-area as tropical forests. While buildings are a contributor to this carbon storage, soils, vegetation, and landfills contribute more significantly to carbon storage. Churkina (2016) also estimated that landfills alone store more carbon (30 GtC) than urban buildings globally (6.7 GtC).

Taking a different approach, Zhang et al. (2020) used multiregional input-output tables to quantify HWP consumption by different sectors, and found that 63 MtC/yr are taken by the construction sector, but the outflow is not quantified.

Several authors assess the carbon storage potential of future scenarios under aggressive adoption of carbon-storing materials. For instance, Churkina et al. (2020) have estimated the carbon storage potential of building structural and enclosure systems of mid-rise timber-framed buildings at the global scale through to 2050. At a regional scale, Nepal et al. (2016) considered the carbon storage potential of the low-rise, non-residential building stock of the US, through to 2060 with the increased adoption of the construction typology. Likewise, Hafner and Rueter (2018a) and Kalt (2018) look at the potential for storing more carbon in residential construction in Germany and Austria, although over very different timescales. The potential for carbon storage in building retrofitting projects in the EU is considered by Pittau et al. (2019) as previously discussed. Peñaloza et al. (2018) analysed scenarios for new construction in Sweden over the next century, and found a total cumulative difference between scenarios of 2 MtC, including both substitution and storage effects. Nygaard et al. (2019) find that increasing timber in construction can make a significant contribution to 2015-30 decarbonisation targets for Oslo and the surrounding area, although the contribution of the storage effect is secondary to the substitution effects. While there are many other studies that focus upon HWP at a regional scale, there is a missing link between the HWP and their use as a construction material. In order to really tackle this question, further primary research may be needed into understanding and quantifying the roles played by different product categories in buildings (e.g. structure, envelope or fit-out), and the different rates at which stocks of material in these roles are turned over in different regions, without relying on defaults.

When evaluating the carbon storage potential of bamboo at the building stock scale in the Philippines, Zea Escamilla et al. (2016) found that in addition to storing 8.7 MtC in the buildings and 1.2 MtC in plantations and the even greater substitution effect, the potential for job creation was higher when glue-laminated bamboo was used in comparison to concrete hollow block construction.

Another theme explored by some, either through MFA or input-output analysis, is the potential of enhancing 'material cascades' (*i.e.*, increasing recycling rates and extending product lifespan) to increase carbon storage in building stock. The Brunet-Navarro et al. (2017) simulation, for instance, shows prolonging product life provides linear improvements, whilst increasing recycling provides exponential benefit. If these strategies are combined, carbon accumulates rapidly beyond 2030, and by 2045 additional carbon storage in wood-based panels would amount to 18 $MtCO_2$/yr. On the basis of their scenario analysis of Canadian timber use, Sikkema et al. (2013) recommend that harvested wood of sufficient quality should be used for sawnwood, then recycled for wood-based panels before going to energy recovery. And exploring a similar theme, Parobek et al. (2019) found a 50% improvement can be made to HWP carbon storage in Slovakia without increasing timber extraction. Evidence is provided that timber is not currently being used to its full quality potential, and a commensurate shift from pulp and paper production towards saw logs should be pursued, although investment and innovation will be needed to deliver on the promise.

The relative significance of this storage compared to population and wider GHG emissions varies significantly between studies, with some studies reporting 2-3 tC/cap of realised or potentially additional storage. Other studies report their scenarios delivering much smaller benefits, with cumulative storage amounting to less than 20% of annual emissions: in other words, the benefits of – carbon storage accumulated over a century, in some cases, is exceeded by emissions from energy consumption in around two months.

Table 4. Carbon physically stored in various construction-related situations (converted from CO2e in some cases). Population data and projections as far as 2050 from worldometers.info (2020) and national CO_2 emissions from energy consumption from IEA (2020).

REGION		ANNUAL CARBON STORAGE				CUMULATIVE CARBON STORAGE				Notes	Reference
		Year	MtC yr^{-1}	tC yr^{-1} cap^{-1}	Share of annual CO_2 emissions	Period	MtC	tC cap^{-1}	Share of annual CO_2 emissions		
	Global					to 2015	6700	0.908	76%	(i)	(Churkina, 2016)
	Global	2050	680	0.0699	5.8%	2020-2050	20390	2.094	175%	(ii)	(Churkina et al., 2020)
	USA					to 2000	900	3.195	78%	(iii)	(Churkina et al., 2010)
	USA					to 2060	33.8	0.089	2%	(iv)	(Nepal et al., 2016)
	Philippines					~2015-2060	8.7	0.060	18%	(v)	(Zea Escamilla et al., 2016)
	EU-28					2018-2100	76.6	0.149	9%	(vi)	(Pittau et al., 2019)
	Austria					2015-2100	2.6 to 23.2	0.28 to 2.54	15 to 133%	(vii)	(Kalt, 2018)
	Germany	Avg 2015-30	0.26-0.44	0.003 to 0.005	0.13 to 0.22%					(viii)	(Hafner and Rueter, 2018b)
	EU-28	2045	4.9	0.0095	0.6%					(ix)	(Brunet-Navarro et al., 2017)
	Switzerland					2016-2216	9.5 to 16	0.97 to 1.63	85 to 142%	(ix)	(Mehr et al., 2018)
	Germany	~2020	0.55	0.0066	0.3%					(ix)	(Budzinski et al., 2020)

Notes

(i) carbon stored in urban areas

(ii) mid-rise timber frame buildings, 2020-2050, aggressive adoption scenario

(iii) snapshot of buildings and furniture in conterminous United States (note, this figure - which includes an allowance for 300 kg of furniture per person - is exceeded by the 2100 Mt of organic carbon stored in SWDS)

(iv) the additional carbon stored by adopting a high wood scenario compared to BAU

(v) Bamboo residential housing scenario after 45 years

(vi) Opportunity for storing carbon in wall retrofits, I-joists and straw

(vii) Residential construction - variation depends mainly on wood construction share of market

(viii) Residential buildings - reference and high timber use scenarios

(ix) Increase in cascading compared to reference scenario

8.0 Conclusions and Outlooks

Buildings provide the most substantial and reliable above-ground storage of bio-based products and their constituent carbon, with studies sometimes centred on the most deeply embedded building layer (the structure), but also extending to the building envelope, fit-out, and – in some cases – the contents. In this review, we analysed 180 studies that considered carbon sequestration and storage in buildings, construction products and in harvested wood products (HWP) in general, as buildings provide the most substantial and reliable above-ground storage of HWP carbon, starting with the most deeply embedded building layer (the structure), but also extending to the building envelope, fit-out, and – in some studies – the contents. We first identified the mechanisms through which construction materials sequester and subsequently store carbon, and then reviewed how carbon storage has been considered at different scales: the material, the building assembly, and the building stock. There has been substantial research activity surrounding the most comprehensive accounting methods to be used when considering biogenic carbon, in addition to characterisation of carbon sequestration at the material-scale. Yet, these research methodologies have not been adopted widely when evaluating carbon storage at larger scales (*e.g.*, building assemblies or building stock). If the paradigm of "buildings as carbon sinks" is to be adopted, careful attention must be paid to the method used to account for the carbon that is sequestered and subsequently stored. There is consensus that using a dynamic life cycle assessment methodology yields more nuanced findings than traditional methods (*i.e.*, GWP100), yet traditional static LCA methods remain commonplace. Although, more recent studies have recognized this need for dynamic accounting methodologies and future studies should include them. Yet, challenges still remain due to the complexities of dynamic LCA, limited availability of dynamic life cycle inventory data and LCA practitioners lacking knowledge about implementing the methodology (to date, dynamic methods have primarily only been used in academic studies).

While the present discourse around treating the building stock as a carbon sink has suggested there exists significant potential, there remains substantial work to be conducted. First, the characterisation of the existing global building stock is lacking, and its future evolution (such as per-capita floor space demand, and adoption of bio-based materials) remains uncertain. Thus, the extent to which buildings can store carbon requires further investigation. Second, current figures for carbon storage in buildings is only a fraction of global carbon emissions: even the more optimistic scenarios add carbon at less than 6% of the rate of current emissions (and in many scenarios, less than 1%, see **Table 4** for details). So, whilst there may be a real and quantifiable benefit, the additional adoption of HWPs cannot make a major contribution until global GHG emissions are reduced significantly. Even when accounting for carbon storage, the widely made case for the increased use of timber is still heavily reliant on substitution benefits. This review elucidates that focus should shift from using HWPs more *extensively*, to instead using HWPs more *wisely* (*i.e.*, shifting towards long-lived construction products) and developing the infrastructure required to support the cascading of HWPs.

HWPs will not be the panacea that some have claimed for decarbonising the built environment. Instead, progress must continue to focus on reducing lifecycle emissions of buildings, not necessarily maximising their temporary carbon storage. Focus should shift from increasing the adoption of HWPs, to the development and adoption of fast-growing bio-based materials for use as structural systems and building envelopes. While these construction materials are not currently widespread, they should be evaluated for their potential to reduce global temperature rise through temporary storage in buildings.

9.0 References

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Author Contributions

FP conceptualised the initial scope of the review. JA, JH, FP, and BD analysed and processed the data behind the review, wrote different parts of the manuscript, and approved the final version.

Competing Interests

The authors declare no competing interests.