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Review

Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches

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Abstract: Wood is increasingly perceived as a renewable, sustainable building material. The carbon it contains, biogenic carbon, comes from biological processes; it is characterized by a rapid turnover in the global carbon cycle. Increasing the use of harvested wood products (HWP) from sustainable forest management could provide highly needed mitigation efforts and carbon removals. However, the combined climate change benefits of sequestering biogenic carbon, storing it in harvested wood products and substituting more emission-intensive materials are hard to quantify. Although different methodological choices and assumptions can lead to opposite conclusions, there is no consensus on the assessment of biogenic carbon in life cycle assessment (LCA). Since LCA is increasingly relied upon for decision and policy making, incorrect biogenic carbon assessment could lead to inefficient or counterproductive strategies, as well as missed opportunities. This article presents a critical review of biogenic carbon impact assessment methods, it compares two main approaches to include time considerations in LCA, and suggests one that seems better suited to assess the impacts of biogenic carbon in buildings.

Keywords: climate change; sustainable buildings; embodied carbon; biogenic carbon; dynamic life cycle assessment; life cycle assessment; wood construction

1. Introduction

It was suggested that to keep warming below 2 °C in 2100 and reach the goals set by the Paris Agreement, building construction must become carbon-neutral or carbon-negative before 2030 [1]. Reaching this objective will require substantial efforts, as the building sector emits up to 30% of global GHG emissions [2]. By implementing adapted and efficient strategies, the large mitigation potential of buildings could be exploited at a low to negative cost using available technologies, while providing other value-added benefits [3]. Otherwise, due to the long life cycles of buildings, current suboptimal practices could be locked in for several decades, which would represent a threat for climate change mitigation [4].

The environmental impacts of buildings can be split into embodied and operational impacts. Here, the term impacts is limited to two common climate change indicators: energy (in MJ) and carbon, which is commonly used in the literature as a substitute for total GHG emissions (in kg CO_{2eq}) [5]. Embodied impacts are influenced by construction practices and the inherent characteristics of building materials; they include all related activities over the building's cradle-to-grave life cycle, from the extraction of primary resources to the disposal of products at the end of life [6–8]. Operational impacts are generated during the use phase for heating, lighting, ventilation and air conditioning (HVAC), and the operation of appliances; they are directly influenced by the habits and behavior of the occupants [9]. Operational impacts are traditionally greater than embodied impacts [8,10–12], but technical improvements and stricter environmental regulations contributed to shift this balance. Embodied energy and carbon now occupy a growing share of a building's total impacts, especially in newer, less energy-intensive constructions [7]. Embodied energy can reach up to 46% of a building's total energy consumption [13]. In contexts where the operational energy is produced from low-carbon sources, the embodied energy of construction materials is of greater importance, and can represent more than 50% of total impacts in some cases [14]. This impact shift highlights the importance of building materials, which must be addressed to maximize the climate change mitigation potential of the building sector [15].

Using more biomaterials is a promising avenue to reduce the climate change impacts of the building sector. Biomaterials are often renewable, locally sourced, and their production and transformation requires relatively low energy. Another key argument in favor of biomaterials is the origin of the carbon they contain, biogenic carbon. Biogenic carbon comes from biological processes. By opposition to fossil carbon, it is part of the fast domain of the global carbon cycle, with much faster reservoir turnover rates [16]. It is subject to relatively fast, two-way exchanges between carbon pools in the atmosphere and the biosphere. On a human timescale, the emission of fossil carbon is a permanent, one-way addition of carbon to the atmosphere. In contrast, the emission of biogenic carbon is part of the contemporary carbon cycle; it does not constitute a long-term net addition in the atmosphere. Three benefits of using biomaterials are increasingly recognized. For the same target operational performance, it can (i) reduce the life cycle GHG emissions associated with material extraction and manufacturing; (ii) temporarily store biogenic carbon in the anthroposphere; and (iii) limit GHG emissions by substituting other, more emission-intensive construction materials. These potential benefits explain why green building rating systems (e.g., LEEDv4) now promote the use of certified harvested wood products (HWP) and other bio-based, reused, recycled and local materials to reduce the impacts of buildings [17], and why several studies advocate that wood buildings can achieve lower embodied and operational carbon than conventional buildings [18–22].

Including wood buildings in integrated biogenic carbon management approaches could also generate additional, necessary mitigation efforts and GHG removals. Forest ecosystems are large terrestrial carbon sinks; they play a critical role in the global carbon cycle [23]. However, under the effect of land-use change or natural disturbances (e.g., insects, diseases, fires), forests can become equally large carbon sources. Such natural disturbances are expected to become more prevalent with climate change [24]. This portends an important threat: If terrestrial carbon sinks were weakened or became net CO_2 emitters, the benefits of other carbon mitigation efforts would be reduced or overwhelmed [25]. Stimulating integrated biogenic carbon management approaches can reduce the risk of forest carbon emissions (fires, insects, etc.); increase carbon sequestration through improved primary productivity; and augment carbon stocks in the anthroposphere as harvested wood products (HWP). Rather than focusing on isolated benefits, integrated management approaches aim to minimize net GHG emissions into the atmosphere [26]. They are described as

$$E = F + P + D, \tag{1}$$

where each term represents the net GHG emissions from (F) the forest; (P) the harvested wood products, bioenergy, end-of-life treatment and decay; and (D) the substitution of alternative fuels or materials [27].

With their large environmental impacts and relatively long lifespan, buildings represent a compelling case for integrated approaches. By sequestering high amounts of biogenic carbon in biomaterials such as harvested wood products (HWP), the built environment could become one of the largest terrestrial stocks of carbon dioxide [28]. Using more biomaterials could also encourage sustainable forest management practices and provide substitution benefits. Actively managing the F, P and D carbon pools through such approaches could contribute to the missing mitigation efforts and carbon removals required to keep global warming below 2 °C in 2100 [29], and provide the greatest combined mitigation potential for forests and wood products [23,25–27,30].

Whether the climate change mitigation potential of using more biomaterials in buildings can be leveraged depends on well-informed, efficient strategies to encourage and adopt best practices. Despite the expected benefits of integrated approaches, assessing their actual contribution to climate change is an ongoing challenge. Life cycle assessment (LCA) is a well-documented, standardized, iterative framework used to assess and compare the environmental impacts of products or services over their life cycle. LCA is regularly applied to construction materials and buildings [10,21,31,32], and is increasingly used in decision-making, policy application and compliance, and building certification systems [13,33]. The increased interest for LCA led to several developments that widened its scope, but also multiplied the availability of subjective methodological choices [34–36]. The life cycle impact assessment (LCIA) of biogenic carbon is one such area where guidance is needed. Despite a mature debate [37,38], there is currently no consensus on how to evaluate the potential life cycle global warming impacts of biogenic carbon emissions in LCA. Modelling those impacts requires a robust understanding of their contribution to atmospheric concentrations and radiative forcing over time. Establishing consensual biogenic carbon evaluation guidelines is necessary to minimize subjective methodological choices and to adequately inform efficient climate change mitigation strategies [35,39]. The life cycle of biomaterials is characterized by periods of GHG emissions and removals; accounting for time can have significant consequences on the results and, in some cases, lead to opposite conclusions [40]. However, the treatment of time in LCA is another area where guidance is needed. Recent approaches allow the inclusion of time considerations in LCA, but this remains uncommon, and is mostly handled on a case-by-case basis [34]. Despite the importance of time aspects for biomaterials and buildings, limited information is available for including time in building LCA [15,41,42]. The primary goal of this article is to present a critical review of biogenic carbon impact assessment methods, to compare two main approaches to include time considerations in LCA, and to identify one that is well suited for the assessment of biogenic carbon in current building LCA practice.

2. Methodology

This article reviews life cycle impact assessment (LCIA) approaches to evaluate the global warming impacts of biogenic carbon. More specifically, it focuses on methods to include time in the LCIA of biogenic carbon in process-based, attributional LCA, which is the most common approach in building LCA [43]. Process-based models describe the exchanges of commodity flows between the processes of a specific product system [44], while attributional LCA evaluates the environmental impacts of the studied life cycle as it exists, generally using average data [45].

To foster a more comprehensive review, a more intuitive, critical review process was combined with systematic queries, which allowed an exhaustive review of the related literature. Critical reviews are less systematic than other approaches to literature reviews, but are useful to differentiate competing schools of thought and provide a strong basis for further research [46]. To reach a sufficient depth of understanding, or conceptual depth [47], relevant literature was added iteratively using a combination of the 'Building blocks', 'Citation pearl growing', 'Successive fractions' and 'Berry picking' search strategies (Table 1) [48].

Table 1. Search strategies used for the critical review of the literature—Adapted from [48].

Building Blocks	Subdividing a search query in multiple items, including variants and synonyms, and then combining these items using Boolean operators.
Citation Pearl Growing	Finding and scanning key relevant citations for relevant terms that might have been excluded from the original search strategy.
Successive Fractions	Sifting databases for small sets of highly relevant articles by successively adding new items to a query using the AND operator.
Berry Picking	Scanning articles for relevant references, citations, authors and journals, then consulting the selected references continuously, in a backward chain.

The first consulted articles described how integrated biogenic carbon management approaches including forests, harvested wood products and displaced emissions can minimize net GHG emissions to the atmosphere [25,27,30]. Relevant articles were then added iteratively through the four search strategies (Table 1). For the building blocks and successive fractions strategies, the keywords synthesized in Table 2 were combined using Boolean operators in different document retrieval systems (Engineering Village, Université Laval's library database Ariane, Google Scholar, Mendeley webservice). Primary keywords defined the core topics of the queries; they were combined with secondary keywords to refine the results. The citation pearl growing and berry picking strategies were then used to identify other relevant authors, journals and articles for the critical review. Research stopped when conceptual depth was deemed satisfactory. This was defined as the point where further iterations of search strategies added no new elements to the overall understanding of the literature within the scope of the review [47]. This point is influenced by practical constraints (time, resources) and is inevitably arbitrary [49], but defining these limitations does not limit the relevance of this review's findings [50]. Sixty-five articles were identified and reviewed through this process.

Table 2. Synthesis of primary and secondary keywords used in the global scope of the review.

Primary Keyword	Life Cycle *	Metrics	Carbon *	Building *
Secondary Keyword	Analysis (LCA) * Assessment (LCA) * Attributional Dynamic * Impact assessment (LCIA)	Emission Global warming Climate change	Accounting Biogenic * Embodied Forest * Footprint Sequestration Storage Substitution	Biomaterials * Construction * Harvested wood products Materials Sustainable Timber Wood

* Keywords used in the systematic queries.

The more intuitive review process was complemented with systematic queries to ensure a thorough verification of related articles, and to confirm the conceptual depth of the review. Keywords marked with an asterisk (*) cover central themes of this review and are not overly restrictive. They were combined in the five following queries in Engineering Village:

1. ((“Dynamic” AND (“life cycle assessment” OR “lca” or “life cycle analysis”)) OR “DLCA”)
2. (1.) AND (“building” or “construction”)
3. (1.) AND (“biogenic” or “forest”) AND “carbon”
4. (1.) AND “biomaterials”
5. (1.) AND (“building” or “construction”) AND (“biogenic” or “forest”) AND “carbon”.

Records were retrieved from the Compendex, Inspec, GEOBASE, GeoRef and Knovel databases for the period 1666–2018. Query 1 returned 1335 records. An overview revealed that several records were either unrelated to desired applications (biomaterials, HWP, buildings, etc.), or restricted the term “dynamic” to life cycle inventory (LCI) or prospective elements (dynamic modelling, programming, simulation, scenario analysis, etc.) unrelated to the scope of the study. Queries 2–5 were more restrictive and returned fewer, more relevant records (Figure 1). Duplicates were excluded, then the detailed records (including titles and abstracts) were screened for eligibility. Records were rejected if they used different meanings of "dynamic" (e.g., in seismic, thermal simulation or energy-related applications); if they clearly used standard LCI and LCIA practice; if they strictly focused on LCI elements unrelated to biomaterials; or if they did not mention using dynamic LCI or LCIA. When the detailed records did not suffice to include or exclude an article from the scope of the study, the full paper was screened using the same criteria. After screening, the remaining 43 articles were included in the review, complementing the 65 articles identified through the search strategies presented in Table 1 (Figure 1).

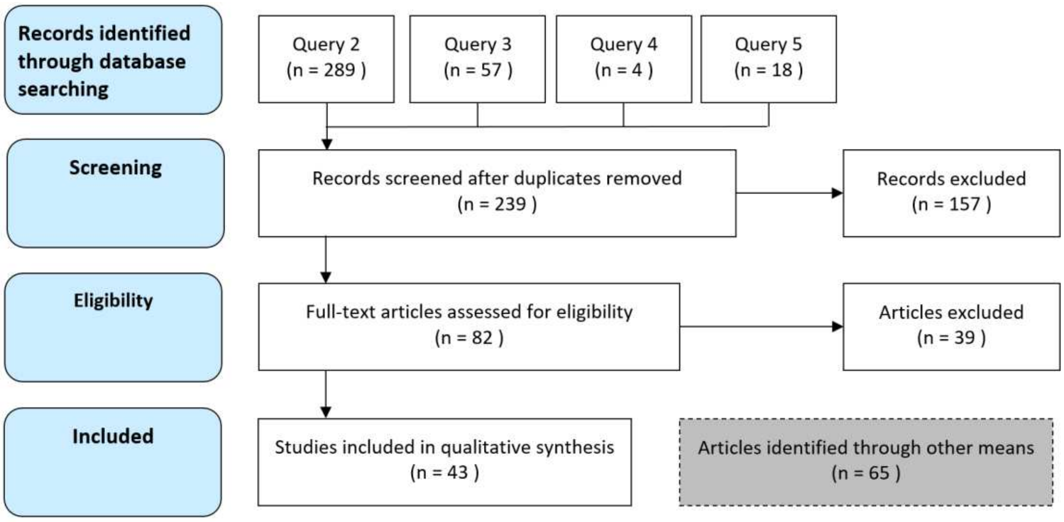

Figure 1. Results of the systematic queries—Adapted from the PRISMA flow diagram [51].

The 108 articles identified through systematic queries and search strategies were further reviewed to identify approaches allowing the inclusion of time considerations in the LCIA of biogenic carbon. In total, 28 of the 43 articles identified through systematic queries (S) and 30 of the 65 articles identified through other search strategies (R) were compared, for a total of 58 potential approaches. Articles using, recommending or updating other existing approaches were grouped together, resulting in a total of 20 different approaches. This process and the identified approaches are further described in Section 3.3. The 50 remaining articles (15 from the systematic review, 35 from the search strategies) did not specifically cover the related approaches; they were excluded from the comparison, but provided background for the critical review of the literature (e.g., [38,52–57]).

3. Critical Review of the Literature

Since biogenic carbon gained interest in the 1990s [58,59], its climate change impacts have been extensively debated [52,57,60–62]. The simplest, first approach was to disregard biogenic carbon entirely, by excluding it from the LCA [63]. Common assumptions were to consider that (i) over the life cycle, biogenic carbon emissions are offset by equivalent removals, for a result of net zero emission; and (ii) that biogenic carbon stocks in the anthroposphere are finite and stable. Assuming biogenic carbon is carbon neutral (i) attributes a characterization factor (CF) of zero to any biogenic CO_2 emission, thus excluding it from the life cycle impact assessment (LCIA). Assuming biogenic carbon is entirely emitted at harvest (ii) means that any new harvested wood product replaces a similar product, resulting in a neutral GHG emission and a net neutral effect on climate change [25]. This prevents any incentive for the temporary storage of biogenic carbon in HWP [64]. The assumptions of carbon neutrality (i) and emission at harvest (ii) were later recognized as oversimplifying [30,65]. However, before further addressing the specific LCIA of biogenic carbon, a synthesis of conventional LCIA practice is presented as a basis for further discussions.

3.1. Conventional LCIA Metrics for Climate Change

The potential impacts of GHG emissions can be aggregated and evaluated at different points of the cause–effect chain of the climate change impact category (Figure 2). Life cycle GHG emissions (e.g., kg CO_2, kg CH_4, kg N_2O) are converted in global warming impacts using an emission metric, and then reported as a midpoint (e.g., cumulative radiative forcing) or endpoint indicator (e.g., malnutrition, extinction of species). Endpoint indicators can also be grouped in damages categories that affect areas of protection that have recognizable value to society (e.g., human health, ecosystem quality) [66]. Endpoint indicators can thus be more relevant for policy making. However, since they are further down the cause-effect chain, they are also more uncertain. Midpoint indicators are currently more common in global warming LCIA practice [55].

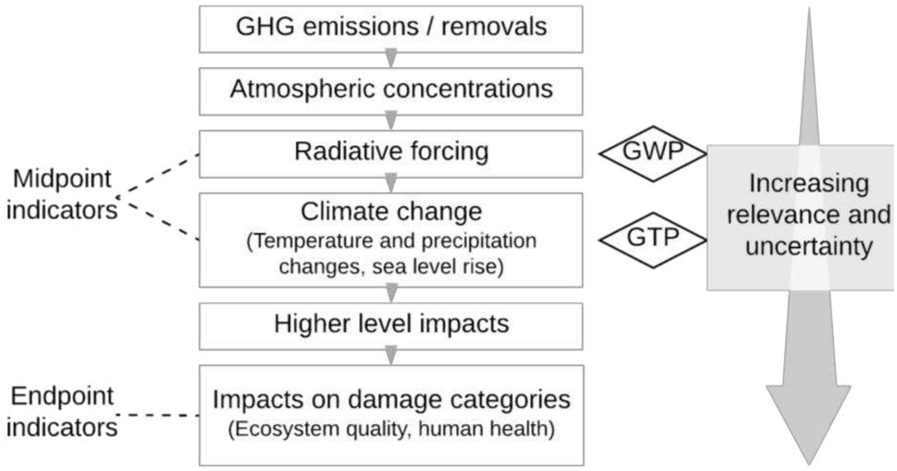

Figure 2. Position of two common metrics, global warming potential (GWP) and global temperature change potential (GTP), on the cause-effect chain of climate change—Adapted from [55,67].

Emission metrics can be broadly categorized by (i) the modelled climate change indicator (e.g., radiative forcing, temperature change, sea level rise, precipitation change); (ii) the desired type of results (absolute or normalized); and (iii) the studied impacts (instantaneous or integrated/cumulative) [54]. Absolute results express the value of a specific indicator; they can be used to compare the impacts of different GHG emissions over time. Normalized results express the relative impact of a given indicator compared to a reference gas, usually CO_2. Instantaneous metrics evaluate the impacts of a GHG emission at a specific point in time, while for the same emission, cumulative metrics express the integrated impacts over time until a chosen time horizon is reached [68]. Other important differences between global warming metrics are the assumptions regarding emission scenarios (constant or variable background emissions), and the time dimension chosen for the analysis (fixed or variable time horizon) [54]. In fixed time horizon (sliding window) metrics, the impacts of GHG emissions are assessed over a given duration, independently of the length of the studied life cycle or the period over which the GHG emissions are assessed. This guarantees an equal assessment of the impacts of all GHG emissions. In variable time horizon (fixed endpoint) metrics, the length of the time horizon changes relative to the last year of the period over which the GHG emissions are assessed. Emissions that occur early in the life cycle are assessed with longer time horizons, and are thus given greater impact. Impacts that occur after the fixed endpoint are excluded from the analysis. This increases the sensitivity of fixed endpoint methods to the choice of time horizon. However, it also avoids inconsistencies when assessing the impacts at any chosen future time horizon; combined with sensitivity analyses, this can be useful for decision-making [54]. This is further discussed in Section 3.3.

Normalized metrics prevail in current global warming LCIA practice [69]. Since its introduction in the first assessment report of the Intergovernmental Panel on Climate Change (IPCC) [70], the global warming potential (GWP)—and more specifically GWP100—is by far the most common emission metric. It measures the cumulative impact of a given GHG emission on the Earth's radiative forcing relative to the impact of a CO_2 emission, over a fixed and predetermined time horizon (e.g., 100 years). However, this inadvertent consensus was based on an illustrative example, rather than the result of conclusive scientific evidence [68,71–74]. Critics of the GWP100 argue that despite being named global warming potential, it does not measure actual warming [75]. Moreover, it can be inaccurate when comparing the impacts of short- and long-lived GHG [76,77]. Global temperature change potential (GTP) is the second most common emission metric; it was suggested as an alternative to GWP. GTP goes one step further down the climate change cause-effect chain by modelling the instantaneous impact of GHG emissions on temperature change. For this reason, it might be more policy relevant [72]. Table 3 categorizes the normalized metrics GWP and GTP in relation to other related metrics: absolute global warming potential (AGWP), absolute global temperature change potential (AGTP), integrated GTP (iGTP) and integrated AGTP (iAGTP).

Table 3. Non-exhaustive list of global warming metrics—Adapted from [55].

	Absolute Metrics		Normalized Metrics	
Climate Change Effect	**Instantaneous**	**Cumulative**	**Instantaneous**	**Cumulative**
Radiative forcing		AGWP		GWP
Temperature change	AGTP	iAGTP	GTP	iGTP

3.2. Time in Conventional LCIA Practice

There are three main time considerations in LCA: (1) The characterization time horizon (hereafter named time horizon), which is the time used in the emission metrics; (2) the period of assessment, which describes the temporal boundary of the studied LCA system; and (3) the life cycle, which is the total duration of the product's life cycle [52]. In conventional LCA practice, for each studied GHG, the life cycle emissions are summed over the period of assessment, then multiplied with their respective characterization factor (CF). The CF is the value of the chosen emission metric for a given time horizon. In the case of normalized emission metrics (e.g., GWP100), the potential impacts of each GHG are then combined to get the total global warming impact in kg CO_{2eq}. This approach can be described as static: It does not consider the influence of time considerations in LCA. Even without considering the issues it poses for biogenic carbon LCIA, this conventional approach to LCIA was challenged. For a given time horizon (TH), emission metrics conventionally result in single, separate indicators for each GHG. Selecting a single combination of emission metric and TH for LCIA is challenging, as the results are sensitive to both parameters. Because of embedded value judgements, the use of a single metric and time horizon for decision-making purposes risks promoting incomplete, suboptimal or counterproductive strategies [56].

Using a variety of metrics can help better represent the short-, mid- and long-term impacts of GHG emissions. Although it is imperfect, GWP100 is still commonly used in LCA [56]. Since it correlates well with a temperature rise in 40 years (GTP40), it is an interesting mid-term indicator for climate change [78,79]. GWP20 has been suggested for short-term impacts, and GTP100 for long-term impacts [54,56,80]. De Rosa et al. [60] also suggested the use of GWP500 since it correlates well with the long-term impacts linked to cumulative warning; however, the IPCC's 5th assessment report does not provide GWP500 values for well-mixed GHGs because of the high associated uncertainties [81]. Cherubini and Tanaka [78] and Levasseur et al. [54] both advocate the use of GWP20, GWP100 and GTP100 for global warming impact assessment; the former also recommends expressing GWP results in CH_4 equivalents (rather than CO_{2eq}) to avoid confusion and better differentiate between short- and long-term impacts. Using shorter time horizons with cumulative metrics can also be an indicator of the rate of temperature change [54]. These recommendations on the climate change impact assessment of GHGs will undoubtedly enhance modelling harmonization and the robustness of LCA results in a decision-making context, and are relevant for the impact assessment of biogenic carbon and for building LCA in general. However, using conventional, fixed time horizon metrics is not sufficient to accurately assess the global warming impacts of biogenic carbon, even if multiple time horizons are used (e.g., 20, 100, 500). Because of the dynamics linked with biogenic carbon emissions and removals, time plays an important role in the LCIA of biogenic carbon. Time considerations such as temporary carbon storage were key elements in the development of biogenic carbon LCIA methodologies, and must be generalized to enhance current biogenic carbon assessment practices.

3.3. Approaches to Include Time in The LCIA of Biogenic Carbon

After first excluding biogenic carbon from the LCIA, developments in biogenic carbon LCIA approaches rejected the assumptions of carbon neutrality (i) and emission at harvest (ii), and acknowledged the potential benefits of temporary carbon storage. These methods also used a static LCI of GHG emissions and conventional CF, but assigned credits based on the duration of carbon storage for a given GHG emission. The Moura-Costa [82] and Lashof [83,84] methodologies are two examples that belong to this second category (Category 2, see Table 4). Both approaches use a fixed time horizon, but assign credits differently. The Moura-Costa gives credits based on an equivalence between ton-years of CO_2 and one ton of CO_{2eq}. Temporarily storing biogenic carbon for 48 years is equivalent to avoiding one ton of CO_2 emissions. The Lashof approach gives credits based on the fraction of impacts pushed outside of the period of assessment by the storage period. Temporarily storing biogenic carbon for a number of years is equivalent to delaying a fossil CO_2 emission by the same number of years [52,53].

According credits for temporary carbon storage was later debated. In 2011, the Expert Workshop on Temporary Carbon Storage for use in Life Cycle Assessment and Carbon Footprinting (hereafter named the Expert Workshop) aimed to identify the most appropriate assessment method. The outcomes of the Workshop are reported in Brandão and Levasseur [53], and synthesized in Brandão et al. [52]; both publications are a good synthesis of the development of biogenic carbon assessment methodologies. During the Expert Workshop, existing approaches were reviewed, and the potential benefits and risks of temporary carbon storage were outlined [52,53]. Temporary carbon storage can postpone climate change; it can buy time for technological progress, capital turnover and learning; it can potentially result in some permanent sequestration; etc. [85,86]. However, by temporarily reducing atmospheric CO_2 concentrations, biogenic carbon storage can lower the CO_2 removal rates of other sinks (e.g., oceans), eventually leading to higher atmospheric concentrations and temperatures when the carbon is later released. It was argued that to fully assess the global warming impacts of biogenic carbon, (i) the instantaneous effect of increased temperature, (ii) the rate of temperature increase and (iii) the cumulative effect of increased temperature must all be considered [87–90]. No consensus was reached at the Expert Workshop regarding how—and if—temporary carbon storage should be considered in LCA, and no methodologies were recommended for the LCIA of biogenic carbon. However, the workshop identified key knowledge gaps and established some common ground in the assessment of biogenic carbon [52,53]:

- Biogenic carbon assessment requires a better understanding of the dynamics of the global carbon cycle;
- The definition of time boundaries for any LCA is highly sensitive and subjective, but temporal issues should be included in the assessment of biogenic carbon;
- For any form of temporary carbon storage, defining assumptions and methodologies clearly and explicitly is important, and both short- and long-term impacts should be considered;
- The use of single metrics (e.g., GWP100) is insufficient, as only the combination of multiple indicators can express the full scale of global warming impacts (cumulative and instantaneous climate effects). No preference was given to having either three mid-point metrics (for impacts i–iii) or a single, aggregated end-point metric.

The Expert Workshop coincided with the development of dynamic approaches—methods to include time considerations in LCA. These dynamic approaches recognize that the global warming impacts of GHG emissions are directly linked with the changes in atmospheric concentrations of GHG over time. Consequently, the neutrality of carbon emissions over a given life cycle does not assure a neutral effect on the climate.

Based on the reviewed articles, dynamic approaches can be further split in two categories. Category 3 describes methods that include system dynamics and time in the LCI (e.g., forest carbon emissions, removals, temporary carbon storage) but uses static, fixed time horizon emission metrics. For example, Levasseur et al. [91] combined the Moura-Costa and Lashof approaches with a dynamic LCI; another example can be found in Smyth et al. [27], where a dynamic LCI including forest dynamics is combined with conventional LCIA metrics. Category 4 describes methods that include the same dynamic elements in the LCI, but also uses dynamic, fixed endpoint CF in the LCIA. Existing biogenic carbon LCIA methodologies can thus be grouped into four categories (Table 4).

Table 4. Synthesis of the four main approaches for biogenic carbon assessment in attributional LCA.

	1. Static LCI and LCIA	**2. Static LCI and LCIA, with Credits**	**3. Dynamic LCI and Static LCIA**	**4. Dynamic LCI and LCIA**
Assumption of Carbon Neutrality	Yes	No	No	No
Assumption of Emission at Harvest	Yes	No	No	No
Credits for Temporary Carbon Storage	No	Yes	No Sequestration and temporary storage are considered in the dynamic LCI.	No Sequestration and temporary storage are considered in the dynamic LCI.
Treatment of Time in LCI	Aggregated as a pulse emission at time 0.	Aggregated as a pulse emission at time 0.	Dynamic	Varies. Some approaches use a dynamic LCI, other include time considerations directly in LCIA.
Treatment of Time in LCIA	Fixed time horizon	Fixed time horizon	Fixed time horizon	Fixed endpoint

In the static LCA framework and in methods that use a dynamic LCI with conventional LCIA approaches, GHG emissions are multiplied by their respective emission metric using a fixed time horizon, then aggregated in a single result. This introduces an inconsistency between the period of assessment and the time horizon chosen for the CF [40]. If different life cycle inventories are compared, e.g., in a comparative LCA of two buildings, then the LCIA results of each building can cover different total impact assessment periods, even if the same time horizons and period of assessment are used. Dynamic approaches that use fixed endpoint DCF (Category 4) avoid these time inconsistencies (Figure 3). The emission metric becomes more sensitive to the chosen TH, as the impacts of emissions that occur after the TH are excluded from the analysis. However, it allows more accurate and flexible sensitivity analyses, and is useful for decision support. Another advantage of fixed endpoint DCF is that although different GHG emission profiles can share the same climate change impacts on a given time horizon, the trajectories to reach this final state can vary. By using fixed endpoint DCF to assess the impacts of GHG emissions, dynamic approaches can help choose between those trajectories to limit undesirable climate change effects, such as the crossing of climate tipping points [62,92,93], i.e., thresholds after which adverse effects can snowball irreversibly, even without further additional forcing [92].

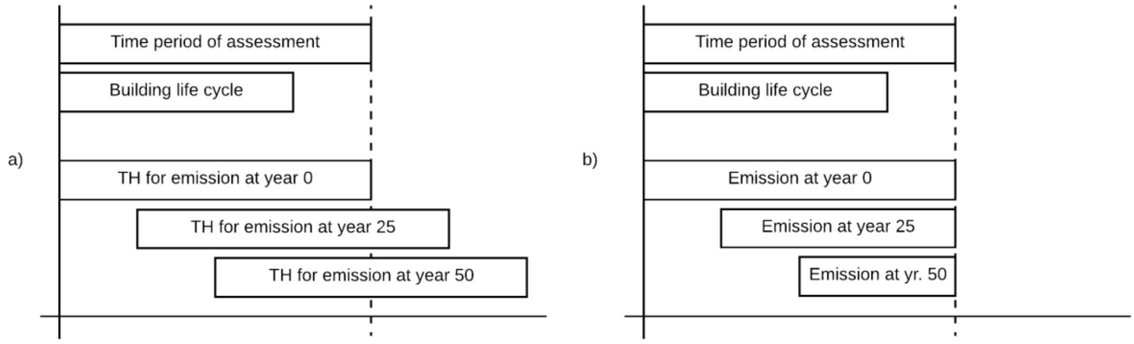

Figure 3. Time horizon covered by the LCIA of GHG emissions for (**a**) fixed time horizon and (**b**) fixed endpoint, for a 75-year building life cycle and a 100-year assessment period—Adapted from [40].

The outcomes of the 2011 Expert Workshop [52,53] still prevail today: There remains no official agreement on the assessment of biogenic carbon in LCA. Despite several LCIA developments, notably dynamic approaches, combining a single fixed time horizon climate metric and a 100-year time horizon remains the most common practice for the LCIA of biogenic carbon. The timing of emissions is not considered in the LCI, biogenic emissions are assessed with a CF of 0, and no credit is given for temporary carbon storage [94]. The current lack of consensus is reflected in technical standards, which complicates the undertaking of LCA and environmental product declarations (EPD) of materials based on HWP [95]. The lack of guidance is also consistently raised as key recurring issues in recent articles [37,38,52,57,60,62,94,96–99]. Another example is the lack of reliable guidelines for establishing displacement factors to calculate the substitution benefits (D) of biogenic carbon. Displacement factors represent avoided fossil carbon emissions; they present a large potential for climate change mitigation [99,100]. However, in the literature, these factors vary greatly. A meta-analysis by Sathre and O'Connor identified a range of displacement factors of −2.3 to 15 tons of carbon (tC), with most values in the range of 1.0 to 3.0 tC, and an average of 2.1 tC (or 3.9 tCO_2 per ton of dry wood used) [101]. Smyth et al. [27] determined displacement factors for the Canadian context and found values of 0.38 tC for sawn wood and 0.77 tC for panels. They revised those factors in 2016, and found a range of 0.45 to 0.89 tC, depending on the product and feedstock scenario [102]. The large range of displacement factors depends on several methodological assumptions, and includes elements of scenario analysis that exceed the scope of attributional LCA; their use in attributional LCA remains controversial [98]. Nonetheless, a consensus is slowly emerging from the literature. Most of the above-mentioned articles recognize: The value of temporary carbon storage, and the necessity to account for it in LCA; the necessity of including all biogenic carbon stocks (e.g., including soil carbon) in LCA; the high sensitivity of results to the timing of emissions and sequestrations; the high influence of the choice of TH and climate metric; and the problems of the current lack of consensus between static and dynamic accounts of carbon fluxes.

By combining a dynamic LCI and dynamic LCIA, Category 4 approaches can better represent the dynamics of biogenic carbon emissions and removals in the forest (*F*), products (*P*) and substitution (*D*) pools; they can also more accurately assess the climate change mitigation potential of integrated biogenic carbon management approaches. The 108 identified articles were reviewed to identify potential Category 4 approaches. Those were required to be usable in process-based, attributional LCA; other types of LCA methodologies were out of scope. The articles were not required to explicitly mention biogenic carbon. They were compared based on their ability to include the timing of emissions, and to assess dynamic global warming impacts. Other metrics, for example the loss of carbon sequestration [103], were out of scope. Articles using conventional, Category 1 or Category 2 approaches were excluded (e.g., [22,39,82–84]), as were the articles that only focused on dynamic LCI elements and omitted LCIA or used static CF (e.g., [27,42,104]). General articles on LCI and LCIA, and reviews mentioning several approaches without recommending any were also excluded (e.g., [38,54–56,105,106]). All excluded articles helped provide context and background information for the comparison.

Fifty-eight articles on Category 4 approaches were compared to identify the ones best suited to include time considerations in the LCIA of biogenic carbon in building LCA. The 58 articles were grouped in 20 different approaches; they are here listed by approach and source (Table 5). Letters *R* and *S* identify if each article was found through search strategies (R) or systematic queries (S). Reviewed articles using, recommending or updating existing approaches are combined and listed for each approach by review type (R or S) to condense Table 5 and enhance readability. However, the listed source and related articles were all equally considered in the comparison. The 20 approaches were compared qualitatively based on their ability to include multiple GHGs; to allow multiple types of emission profiles over the life cycle; to be usable for multiple products (e.g., biofuels, bioenergy, storage in HWP); and to handle different types of metrics to assess different climate change impacts. Most reviewed approaches use a combination of dynamic LCI with absolute metrics like the cumulative radiative forcing (AGWP) and the global mean surface temperature change (AGTP) [107–116]. Less common approaches include physically discounting LCI emissions [117,118] or including policy-related targets such as climate tipping points [62,93] or emission scenarios [73]. Some approaches are also specifically meant for specific applications, such as the LCIA of biofuels [119–121] or the amortization of emissions [122,123]. A dynamic LCA framework includes dynamic scenario analysis with dynamic LCI and LCIA in building LCA [41,124], relying on the time-adjusted warming potential (TAWP) approach [116] for the LCIA. Nonetheless, two approaches stand out by their flexibility (their ability to include all GHG and produce several metrics) as well as their impact: After their publication, both methods have been further enhanced and applied to multiple case studies in different fields, representing half of the reviewed articles. Dynamic LCA (DLCA) [40] and GWP_{bio} [125] also stand out from other methodologies by how they are calculated. DLCA streamlines the process of combining a dynamic LCI with DCF by using a matrix approach, while GWP_{bio} allows the use of a static LCI by including all time considerations in the dynamic LCIA. Both DLCA and GWP_{bio} are further compared in Section 4, and their differences are studied from a building LCA perspective to review their potential application in industry practice.

Table 5. Summary of reviewed dynamic approaches.

Approach [1]	Source *		Time Consideration	Other Related Articles [2]			Total Reviewed Articles	Period Covered by Articles
DLCA	R	Levasseur et al. (2010) [40]	Dynamic LCI and LCIA	S R	10 4	[15,63,91,94,96,126–130] [131–134]	15	2010–2018
GWP_{bio}	R	Cherubini et al. (2011) [125]	Static LCI, Dynamics in LCIA	S R	5 8	[65,94,135–137] [18,61,67,69,71,98,138,139]	14	2011–2018
Dynamic LCA Framework for Buildings	S	Collinge et al. (2013) [41]	Dynamic LCI and LCIA	S R	3 -	[124,140,141] -	4	2011–2014
Time-dependent climate impact	R	Ericsson et al. (2013) [107]	Dynamic LCI and LCIA	S R	2 -	[108,109]	3	2013–2016
Discounted Global Warming Potential	S	Petersen & Solberg (2002) [118]	Dynamic and LCIA (infinite TH)	S R	1 -	[117] -	2	2002–2004
Relative Radiative Forcing Commitment	S	Kirkinen et al. (2008) [119]	Dynamic LCI and LCIA	S R	1 -	[120] -	2	2008–2010
Time Correction Factor	R	Kendall et al. (2009) [123]	Dynamic LCI and LCIA	S R	- 1	- [122]	2	2009–2012
Time-Dependent Radiative Forcing	R	Sathre & Gustavsson [113]	Dynamic LCI and LCIA	S R	1 -	[112] -	2	2012–2014
Surface Temperature Response	R	Giuntoli et al. (2015) [114]	Dynamic LCI and LCIA	S R	1 -	[115] -	2	2015–2016
Climate Tipping Potential	R	Jørgensen et al. (2014) [93]	Dynamic LCI and LCIA	S R	- 1	- [62]	2	2014–2015
Fuel Warming Potential	R	O'Hare et al. (2009) [121]	Dynamic LCI and LCIA	S R	- -	- -	1	2009
Time-Adjusted Warming Potential	R	Kendall (2012) [116]	Dynamic LCI and LCIA	S R	- -	- -	1	2012
GWP_{biouse}	R	Pingoud et al. (2012) [142]	Static LCI, Dynamics in LCIA	S R	- -	- -	1	2012
Adjusted GWP_{bio}	R	Holtsmark (2013) [143]	Static LCI, Dynamics in LCIA	S R	- -	- -	1	2013
$GWP_{bio, product}$	S	Helin et al. (2016) [144]	Static LCI, Dynamics in LCIA)	S R	- -	- -	1	2016
Differential climate impact	S	Aracil et al. (2017) [110]	Dynamic LCI and LCIA	S R	- -	- -	1	2017
Dynamic GWP and GTP	R	De Rosa et al. (2018) [60]	Dynamic LCI and LCIA	S R	- -	- -	1	2018
Net climatic impact	S	Kipeläinen et al. (2012) [111]	Dynamic LCI and LCIA	S R	- -	- -	1	2012
Time-dependent GTP	R	Shine et al. (2007) [73]	Dynamic LCI and LCIA	S R	- -	- -	1	2007
Dynamic GWP and GTP	R	Peters et al. (2011) [68]	Dynamic LCI and LCIA	S R	- -	- -	1	2011

* The source describes if the article was identified through (S) systematic queries or (R) search strategies. [1] In absence of an official name for some approaches, a name was selected from the text or from the recommended emission metric(s). [2] The listed articles are reviewed articles that either use, recommend or update the approach.

4. Comparing Two Biogenic Carbon LCIA Methods

4.1. The Dynamic Life Cycle Assessment (DLCA) Framework

Dynamic LCA was developed as a generalization of the Fuel Warming Potential (FWP), a metric developed for biofuels [121]. This comprehensive framework aims to solve the inconsistency and time-sensitivity issues of static approaches by including temporal considerations in LCA. It can be applied to any emission profile, any GHG and, potentially, any impact category, provided CF are available [55]. The DLCA approach is synthesized here, and the full description can be found in the original article [40]. DLCA was later applied to the temporary storage of biogenic carbon [52,53,63,91]. Other applications and adaptations of DLCA can be found in [15,60,94,96,126–134].

In DLCA, a dynamic or time-differentiated life cycle inventory (dynamic LCI) is paired with dynamic characterization factors (DCF) using a fixed endpoint. The life cycle impact assessment (LCIA) results in real-time impact scores for different time horizons [40]. Compared to the more usual fixed time horizon approach, DLCA can thus significantly affect the results of LCA [40]. Contrarily to conventional LCI, which aggregate all emissions over the life cycle in a single pulse emission for each GHG, dynamic LCI are distributed over time. The emission profile is obtained by a bookkeeping approach, by tracking all emissions and removals for all GHGs and for every year of the life cycle [98]. DCF is then calculated, by integrating the absolute global warming potential (AGWP) equation for each GHG continuously through time (Equation (2)) [40,63]. The DCFs represent "the cumulative radiative forcing per unit mass of GHG released in the atmosphere since the emission" (W yr m^{-2} kg^{-1}) [40]. The instantaneous DCF for each year following an emission is obtained by dividing the time scale into one-year increments (Equation (3)). This results in specific DCF per year, per GHG *i*. To calculate the global warming impacts of a given emission profile, the dynamic LCI results (total annual emissions) for all GHGs are first multiplied by their respective DCFs, then summed over the whole life cycle (Equation (4)). The result is an instantaneous measure of the radiative forcing caused by every GHG emission over the full life cycle, $GWI_{inst}(t)$ (W yr m^{-2}) [40]. Equation (5) can then be used to calculate the total cumulative global warming impacts, $GWI_{cum}(t)$ (W yr m^{-2}) [63].

$$DCF_i(t)_{cumulative} = AGWP_i(t) = \int_0^t a_i\,[C_i(t)]dt \tag{2}$$

$$DCF_i(t)_{instantaneous} = \int_{t-1}^t a_i\,[C_i(t)]dt \tag{3}$$

$$GWI_{inst}(t) = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^t [g_i]_j \cdot [DCF_i]_{t-j} \tag{4}$$

$$GWI_{cum}(t) = \sum_{j=0}^t GWI_{inst}(j) \tag{5}$$

In Equations (2) and (3), $C_i(t)$ describes the residual atmospheric concentration of GHG *i* following a pulse emission (kg kg^{-1}), and a_i represents the radiative efficiency (RE) of GHG *i*, or the instantaneous radiative forcing per unit mass increase in the atmosphere (W m^{-2} kg^{-1}). For CO_2, $C(t)$ is given by a sum of exponentials. Multiple models are available [81], but using average models such as the one presented in Joos et al. [145] was advocated to be more robust and reliable than selecting specific models [146,147]. For other GHG, $C(t)$ is modelled using an exponential decay based on the perturbation lifetime [81]. The RE of GHG is available in Myhre et al. [81]; for example, the RE for CO_2 (considering atmospheric concentrations of 391 ppm) is 1.7517×10^{-15} W m^{-2} kg^{-1}. In Equation (4), g_i is the life cycle inventory (LCI) result for year *j*, and DCF_i the yearly DCF for GHG *i* [40].

4.2. GWP_{bio}, a Metric-Based Alternative to DLCA

The biogenic Global warming potential, noted GWP_{bio}, was specifically developed to challenge the common simplifying assumption that carbon flux neutrality equals climate neutrality, and to provide a more accurate assessment of the global warming impacts of biofuels. GWP_{bio} is a LCIA method to include time considerations in a DCF (or emission metric). A short description of the method is given here; the exact description can be found in the original article [125]. The approach was refined in further articles, and adapted to include the temporary storage of biogenic carbon and albedo [61,65,67,69,71,98,135,136,138,139]. The possible inclusion of albedo is an interesting advantage of GWP_{bio}, as albedo can have a strong contribution on radiative forcing [138], but it is currently generally out of scope of most LCIA methods for global warming [55,68]. Examples of application of the GWP_{bio} approach can be found in Røyne et al. [94]; Skullestad et al. [18]; Tellnes et al. [148]; and Mehr et al. [137].

Other authors also suggested adaptations of GWP_{bio}. GWP_{biouse} was developed to link the GHG impacts of biomass life cycles with equivalent fossil fuel alternatives; it includes the impacts of temporary storage and substitution benefits [142]. $GWP_{bio,\ product}$ was suggested as an alternative to include temporary storage, but exclude substitution, based on the change in atmospheric carbon concentrations between a harvest- and no-harvest-scenario [144]; the method uses similar assumptions as that of Holtsmark [143]. Although the GWP_{biouse} and $GWP_{bio,\ product}$ approaches might be useful in their respective contexts, they both include elements of scenario analysis in the calculation of impulse response functions (IRF). While technically feasible, this parts with the original definition of IRF, which describes the residual atmospheric concentration of a given GHG following a pulse emission [145,149]. Consequently, using the regular formulation of GWP_{bio} is suggested here.

GWP_{bio} uses a conventional LCI, and computes biogenic-carbon-specific CF using the mathematical properties of impulse response functions (IRFs). IRFs can fully describe the response of linear and time-invariant systems to external perturbations; the convolution integral of an IRF with any input provides the output of the described system [150]. IRF is useful to characterize the behavior of complex carbon cycle models of the main CO_2 sinks, and the ocean and terrestrial biosphere [146,151]. The IRF is "a first-order approximation how excess anthropogenic carbon is removed from the atmosphere by a particular model" [145]. The carbon cycle-climate systems are nonlinear, and the IRF for CO_2 is not invariant, but varies with the magnitude of the carbon emissions [145,152]. However, for sufficiently small CO_2 emission pulses (<100 GtC) with approximate constant background concentrations, the IRF is found to be linear and is a good approximation [145,146,150]. In the GWP_{bio} approach, the IRF of biogenic CO_2 emissions from regenerative biomass systems is described by a mathematical convolution of the emission function (related to the HWP) and the biomass regrowth response (related to the forest carbon emissions and removals) with the IRF of fossil CO_2 (Equation (6)) [98,138]. This approach potentially introduces a small form of double counting for vegetation carbon sinks; however, it should not be the case for carbon cycle models that do not include forest management or bioenergy production [125].

$$f(t) = \int_0^t \left(C_0 e(t')_i y_{CO_2} - C_0^* NEP(t')_i y_{CO_2}\right)(t-t')dt' \tag{6}$$

For a given HWP, *e(t)* is the distributed GHG emission profile (e.g., Gaussian, Dirac delta, Gamma, Chi-Square) including temporary storage. *NEP(t)* is the net ecosystem productivity of the associated biomass resource; it includes net primary productivity (NPP), the carbon sequestration through biomass growth [98], and heterotrophic respiration (Rh). NEP values can be estimated, modelled or measured directly [67]. Another option is to use biomass growth models (e.g., the Schnute model [153], which is identical to the Chapman-Richards function [154]). Both functions *e(t)* and *NEP(t)* are normalized to the unit emission profile [98]. Function *y(t)* is the impulse response function for the carbon cycle climate model [69,125]. The result, *f(t)*, represents the atmospheric decay of the CO_2 emissions. It describes the residual fraction of GHG in the atmosphere following an emission.

The coefficients C_0 and C^*_0 are scaling factors for the intensity of the emission and removal flux [65,135]. When $C^*_0 = 1$, the system is carbon neutral, meaning the studied stand is assumed to sequester the same amount of carbon it contained over the rotation period. C^*_0 values smaller or greater than one indicate that the stand sequesters a smaller or greater amount of carbon over the rotation period [139]. Similarly, the C_0 scaling factor can adjust the size of the biogenic carbon pulse emitted at the end of life of the product.

This approach can be used to calculate various emission metrics (e.g., GWP_{bio}, GTP_{bio}) using a fixed endpoint for the TH [125]. For example, GWP_{bio} is the ratio of the AGWP of IRF *f(t)* and *y(t)* over a given time horizon (Equation (7)):

$$GWP_{bio} = \frac{AGWP_{bioCO_2}}{AGWP_{CO_2}} = \frac{C_0 \int_0^{TH} \alpha_{CO_2} f(t)dt}{C_0 \int_0^{TH} \alpha_{CO_2} y(t)dt} \quad (7)$$

where α is the radiative efficiency (W m^{-2} kg^{-1}), *f(t)* is the biogenic IRF, and *y(t)* is the fossil CO_2 IRF (see Section 4.1). The resulting DCF can then be multiplied with "the direct CO_2 emissions from biomass combustion to get their relative contribution to global warming in terms of kg CO_{2eq}" [125].

GWP_{bio} provides a simple approach to assess the dynamic impacts of biogenic carbon. Despite being named after its initial function, assessing the impacts of biogenic emissions, GWP_{bio} can also be used in other contexts. For instance, GWP_{bio} can be used to study the dynamic impacts of fossil carbon emissions over the life cycle if carbon removals are included in the emission profile. Furthermore, assuming a case where the timing of carbon fluxes is important for fossil CO_2 (e.g., the carbonation of concrete), the same method could be used to derive a dynamic GWP factor assessing the CO_2 emissions and removals over the product's whole life cycle. The adapted metric could be called dynamic GWP (GWP_{dyn}) since no biogenic emissions are involved.

A Note on Potential Inconsistencies When Using GWP_{bio}

Selectively applying GWP_{bio} to biogenic carbon emissions simplifies the characterization of biogenic impacts, but it also implies that other processes are not modelled dynamically. For example, if the CFs developed by Guest et al. [98] are used to assess the impacts of biogenic emissions, then only those emissions are treated dynamically. This raises a consistency issue: The impacts of biogenic emissions are assessed using fixed endpoint metrics (GWP_{bio}), while the impacts of fossil emissions are assessed using fixed time horizon metrics (e.g., GWP100). Final aggregated results would include both dynamic and non-dynamic impacts (kg CO_{2eq}), and would combine results from different time horizons for the same period of assessment. This partially reintroduces the time inconsistencies described by Levasseur et al. [40].

One solution to this consistency issue is to consider the GWP_{bio} method as a simplification with associated uncertainties. The consistency issue raised in Levasseur et al. [40] is introduced when the impacts of GHG emissions are evaluated using metrics with time horizons that exceed the period of assessment selected for the study (Figure 3). For example, in a study of the impacts of a given LCI on climate change in 2100, evaluating any GHG emission occurring after year 0 using GWP100 would result in an inconsistency. The inconsistency would be small for early emissions and progressively larger for later emissions, with maximal inconsistency for the impacts of a GHG emission occurring at year 2100. The impacts would be included in the results, although they occur between 2100–2200. However, in a case where all GHG emissions occurred at year 0, there would be no inconsistency. This illustrates how the inconsistency introduced by selectively applying GWP_{bio} to biogenic GHG emissions might be partly mitigated by the LCI profiles of most non-biogenic building materials (e.g., steel, concrete). Those materials often have long lifespans and low replacement rates; most of their GHG emissions are emitted early in their life cycle, during material extraction and production. Their emission profiles are similar to the pulse emission profile used in conventional metrics (e.g., GWP100). Consequently, the simplification of using GWP might not overly affect the impact assessment results. Due to the IRF of fossil CO_2, in dynamic methods, maximum weight is given to early emissions; the weight then decreases as the emissions get closer to the studied TH. In a case where 100% of GHG emissions are emitted at year 0, with no GHG removals and no replacements over 100 years, then GWP100 is equal to GWP_{bio}100. Furthermore, no time inconsistency is induced by using the GWP 100 CF as both profiles end at the same TH. A conceptual representation of this argument is presented in Figure 4. The normalized curves for the radiative forcing, AGWP and AGTP of three emission profiles (pulse, concentrated and distributed) are shown. The pulse emission scenario represents a static emission of all carbon at year 0, modelled using a Dirac delta function; the concentrated emission scenario is modelled after a Gamma probability distribution function, a common distribution for estimating lifetimes. It represents the emission of 95% of all carbon within the first five years, with a peak of emissions at year one [155]. The distributed emission scenario is calculated using Equation (6) where *e(t)*, the CO_2 emission of the product, is modelled using a chi-square distribution around year 75; *NEP(t)*, the forest carbon emissions and removals, are modelled considering that the same quantity of carbon is sequestered over a rotation period of 70 years. NEP values are considered positive (net CO_2 emissions) in the first years of the rotation period. The radiative forcing, AGWP and AGTP are then computed for each emission profile [81,105,106].

These three scenarios are simplified and do not model the LCI of actual construction materials. However, the concentrated emission profile is conceptually similar to the life cycle emissions of non-biogenic structural materials, while the distributed emission profile could represent the life cycle GHG emissions of structural or other long-lived harvested wood products.

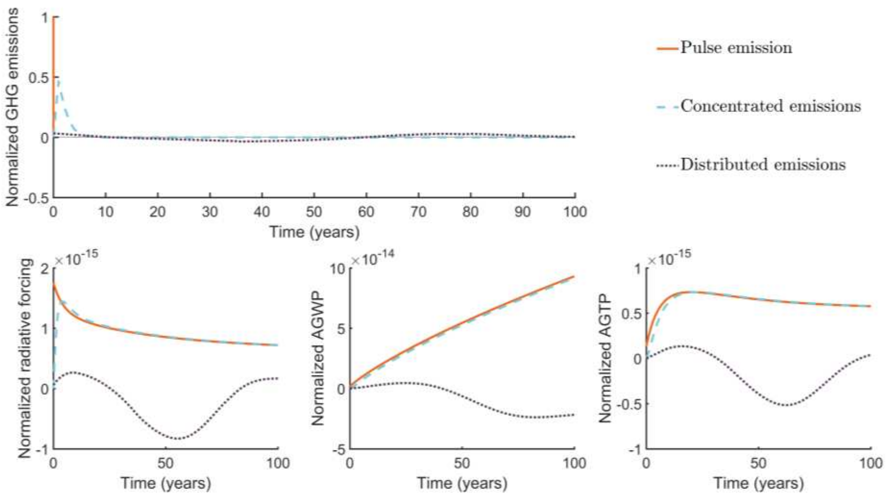

Figure 4. GHG Radiative forcing, AGWP and AGTP for pulse, concentrated and distributed GHG emission profile.

For less-dynamic emission profiles (concentrated emissions), AGWP and AGTP curves are similar to those obtained for static metrics (pulse emission). However, important differences can be seen for more dynamic emission profiles (distributed emissions). Resulting GWP and GTP values for 20- and 100-year time horizons are presented in Table 6. In most cases, for identical time horizons, using GWP is more conservative than using GWP_{bio}. For materials with a high proportion of emissions early in their life cycle, using a static approach might thus be a relatively accurate, conservative approximation. However, for materials with dynamic LCI profiles, using static approaches might be overly conservative, especially if carbon is sequestered early in the life cycle. Of course, for all materials, additional parameters such as material maintenance and replacements, recycling assumptions, carbon removals and end-of-life scenarios could significantly affect the results and might introduce time-related inconsistencies. Materials with such dynamic emission profiles should be selectively assessed using GWP_{bio}. These observations are limited to metrics using the assumption of constant background CO_2 emissions, which is representative of current practice.

Table 6. Dynamic global warming potential (GWP_{bio}) and global temperature change potential (GTP_{bio}) for three emission profiles using 20- and 100-year time horizons.

	GWP20	GWP100	GTP20	GTP100
Pulse Emission	1	1	1	1
Concentrated Emissions	0.91	0.98	0.99	1.00
Distributed Emissions	0.16	−0.23	0.18	0.06

This example illustrates how exclusively applying GWP_{bio} to processes with highly dynamic profiles (e.g., timber) can provide more accurate LCIA information. It also illustrates how the associated uncertainties could be mitigated and evaluated. These observations are consistent with results from Pinsonnault et al. [134] on the addition of temporal information to unit processes in the background of LCI databases. In their study, adding time information to background unit processes affected the global warming impact results by more than 10% in 8.6% of the studied systems [134]. In most cases, the difference was a reduction of global warming impacts. The wood and biofuels sector showed the most sensitivity to the addition of time information to background unit processes because of the large influence of carbon removals (biogenic carbon sequestration) on the climate change category scores [134]. These results indicate that adding time information to some processes might not be necessary, but that it can be highly relevant in other cases. Adding time information to a limited selection of processes using GWP_{bio} might thus be a sufficiently close approximation of a full DLCA.

4.3. Comparison of Both Dynamic Approaches

DLCA and GWP_{bio} are two interesting alternatives to improve biogenic carbon assessment practices, and it is impossible to recommend one approach over the other for all applications. Both approaches have successfully been applied to model temporary carbon storage in LCA. Despite methodological differences, DLCA and GWP_{bio} are expected to provide equivalent results (personal communication with Pr. Francesco Cherubini, 2017–04–20), although their respective uncertainty ranges may vary. To the authors' knowledge, the only existing case study comparing the two approaches resulted in comparable, but slightly larger values for GWP_{bio} (in kg CO_{2eq} m^{-2} of living building area) [94]. By using a fixed endpoint time horizon, both approaches avoid the inconsistencies of conventional methods [40], but are highly sensitive to the choice of the time horizon. In DLCA and GWP_{bio}, pushing emissions further in time results in lower impacts, and pushing emissions out of the period of assessment results in no impacts at all [61]. This infringes the intergenerational equity concept; sensitivity analyses with different time horizons (short-, mid- and long-term) are therefore essential. Reporting GHG emissions and impacts of the studied life cycle that occur after the period of assessment as a memo item could also help support decision making to prevent undesirable outcomes.

One fundamental difference between DLCA and GWP_{bio} is that the former is a complete LCA framework, while the latter is an emission metric. DLCA does not explicitly differentiate biogenic CO_2 from fossil CO_2. Biogenic CO_2 is treated like all other GHGs in impact assessment: CF is obtained by a dynamic adaptation of regular metrics such as GWP or GTP. In DLCA, the difference between biogenic and fossil CO_2 thus only results from the different emission profiles of the dynamic LCI. Conversely, GWP_{bio} was specifically developed to assess the impacts of biogenic carbon. It uses a static LCI, but applies a new CF to assess the impacts of biogenic CO_2 emissions for the emission profile of each process over the life cycle; other GHG emissions are not necessarily treated dynamically.

DLCA can theoretically be extended to all impact categories and emissions metrics, it includes time considerations for all processes over the life cycle, and it treats all GHGs and emission profiles equally. It is a general and robust framework. However, from a professional practitioner's or a designer's point of view, it might be more complex since it relies on dynamic LCIs. Obtaining dynamic LCIs for all processes requires large amounts of data that are currently unavailable in major LCI databases. To solve this issue, Beloin Saint-Pierre et al. [131,132] suggested the use of the Enhanced Structural Path Analysis (ESPA) method to derive dynamic LCIs using a product of convolution inspired by the structural path analysis and power series method. This could eventually facilitate the application of DLCA. Meanwhile, the wider use of DLCA in current practice is impeded by the data, time and expertise requirements.

By using IRFs to include temporal information directly in LCIA emission metrics and by relying on conventional LCIs, GWP_{bio} is arguably simpler. The approach could theoretically be extended to all processes, and would then be similar to DLCA. However, doing so would require calculating different emission metrics for every combination of process and emission profile, for example in a case where multiple instances of one material have different expected emission profiles (e.g., material replacements). This would lead to a multiplication of processes in conventional LCA practice. For a fully dynamic study, GWP_{bio} might thus become more complex, and DLCA might be preferable. Based on previous work by Guest et al. [98], one potential solution to this issue would be to use a property of IRF to model the impacts of choosing a type of product as a whole. IRF fully characterize the response of linear, time-invariant systems, and the global carbon cycle-climate models can be considered linear. Consequently, the biogenic IRF calculated using Equation (6) can provide the output *f(t)* for any combination of *e(t)* and *NEP(t)*. In the case of material replacements, the respective emission profiles for each replacement could be combined in an emission profile associated with using the HWP over the life cycle. The GWP_{bio} approach could then be applied normally, which would help limit the multiplication of processes in the LCA.

Another potential use of GWP_{bio} would be to selectively apply it to biogenic carbon emissions or processes with very dynamic emission profiles. This would provide a much simpler way to include dynamic considerations in LCA, but such an approximation is likely to introduce additional uncertainty compared to a full DLCA. One additional benefit of the GWP_{bio} approach is that CF stay stable for identical emission profiles. For instance, if growth, emissions and end-of-life assumptions are the same for two bio-based products over their life cycles, the resulting CFs will be identical. This is an interesting argument for the building industry: CFs could be reused between projects when HWP are similarly sourced and have the same expected lifespan, or manufacturers could provide pre-calculated CFs for standard life cycle assumptions (growth, rotation period, common end-of-life and recuperation scenarios, etc.). Practitioners could then use their LCI data and the exiting CFs to quickly get results with relative accuracy. As an example, the CFs presented in Guest, Cherubini, et al. [61] have been directly used in other studies [94,148].

The additional complexity of implementing dynamic approaches like DLCA and GWP_{bio} in conventional LCA software can be an obstacle to a rapid adoption of dynamic biogenic carbon assessment approaches in current practice. In fact, several current developments destined for practitioners adopt the opposite approach: They aim at reducing the complexity of LCA, for example by including it in Building Information Models (BIM) with add-ons like Tally [156] or UBUBI [157,158], or by using parametric tools [159,160]. To the author's knowledge, Temporalis, the dynamic life cycle assessment module of Brightway2, is the only available LCA tool dedicated to dynamic approaches. Contrarily to conventional LCA software, it relies on Python programming rather than a more intuitive, 'What You See Is What You Get' (WYSIWYG) graphical user interface (GUI). However, documentation is available to facilitate its use [161] and the free, open source LCA software Activity Brower is also available as a GUI for Brightway2 [162]. The other option to implement dynamic approaches is to calculate the DCF for DLCA and GWP_{bio} separately, as it is currently not possible to implement the functions behind these factors in conventional LCA tools (e.g., SimaPro, OpenLCA). For DLCA, the CFs can be computed using the free online spreadsheet tool $DYNCO_2$ [163]; a programming script was also published in the Supplementary Materials of Pittau et al. [128]. For GWP_{bio}, the CFs can be calculated by using programming tools. Because DLCA rely on dynamic LCIs, all dynamic calculations must be made outside of conventional LCA software. Since GWP_{bio} uses a static LCI, the CFs can be manually added in conventional software, by modifying existing LCIA methods. However, for large numbers of processes (e.g., in complex building LCAs including several harvested wood products), this manipulation is inefficient and might lead to accounting errors. Programming and the use of probability density functions to model GHG emissions could help alleviate data requirement and implementation problems with DLCA and GWP_{bio}. However, since GWP_{bio} includes all dynamic information in the emission metrics, it would remain easier to implement in conventional LCA practice and software (e.g., SimaPro, OpenLCA).

Guinée et al. [35] emphasized the linkages between questions and approaches, implying that some approaches are more adapted to specific questions than others. When the required data is available, DLCA provides the most general way to assess the dynamic climate change impacts of biogenic carbon, especially in cases where several or all impact categories require consideration of time aspects. Its complete framework is potentially better adapted for academic research and LCA development, or to be included in future guidelines and methodologies to support more consistent policy making. However, because of its additional complexity and need for resources, DLCA might not *yet* be suited to the needs and constraints of field research by stakeholders from the industry. Even though accounting for all C fluxes dynamically is ideal, GWP_{bio} might be more useful when resources are constrained or when dynamic LCI data is hard to obtain. Because it includes time considerations in the LCIA and can be selectively applied to relevant processes, GWP_{bio} could be used as a useful approximation of DLCA in industry practice [94], and could be more easily implemented in conventional LCA software. It could also be used to include time considerations in simplified LCAs and carbon footprints, as well as BIM-related or parametric tools that use static LCIs. This could encourage a faster adoption of dynamic approaches by practitioners. The characteristics of GWP_{bio} might also be well adapted for an application in the environmental product declarations (EPD) of construction materials containing biogenic carbon. To allow the customization of EPD results to different building LCA, there is a need for concise, explicit reporting of assumptions [95]. With the GWP_{bio} approach, rather than reporting LCI data, it would be possible to fully describe the relevant biogenic carbon LCI and LCIA assumptions using only the functions and coefficients described in Equation (6). By clearly reporting the assumptions used for the C_0 and C^*_0 scaling factors, the $e(t)$ distribution function and the $NEP(t)$ regrowth emissions and removals function, it would be possible for practitioners to tailor the related EPD results to their needs.

4.4. Implications for Current Building LCA Practice

Giesekam and Pomponi [28] identify the lack of guidance on carbon sequestration in biogenic materials as one of the three main knowledge gaps in building LCA. The emerging consensus in favor of dynamic approaches can help bridge knowledge gaps in both building LCA and biogenic carbon assessment. However, there are concerns regarding how to include dynamic LCI and LCIA approaches in building LCA without increasing their complexity. Buildings are one of the most complex applications of LCA [13,164,165]. They have long lifetimes and contain many materials, each with varying lifetimes and production processes; they change in form and function throughout their lifetime, due to maintenance, alterations and retrofits; they also involve a large diversity and quantity of stakeholders. This results in ambiguous system boundaries in LCA, introduces greater scenario uncertainty (e.g., end-of-life scenarios) and lowers the predictability of variables and parameters. Globally, the complexity of building LCA requires substantial additional efforts in terms of data collection, analysis and interpretation [8].The fact that several of these parameters vary from a country to another also makes evaluation, comparison and benchmarking more difficult [13,166–169].

A recent meta-analysis observed large variance in the LCA results of very similar buildings [170]. Methodological issues and subjective choices generally introduced greater variability than project characteristics (building type, construction materials, size, climate zone) in building LCA. Part of these large variances can be directly attributed to biogenic carbon assessment. Using different LCA approaches, the same case study with identical initial data can lead to opposite conclusions [170]. Thi means that in its current state, building LCA is too unreliable to provide suitable data for decision making, and that existing building LCAs "do not offer solid background information for policy making without a deep understanding of the premises of a certain study and good methodological knowledge" [170]. It is consequently very important to aim for more reliable and explicit methods, both for building LCA and biogenic carbon assessment.

Dynamic approaches are useful to assess the impacts of biogenic carbon, but their additional complexity can represent an important obstacle for their application in building LCA [13]. This reveals a discrepancy between the needs for better carbon assessment to ensure sustainable building practices and decision making, and the need for simpler LCA and footprint tools for the industry. Further LCA developments could enhance this effect by contributing to the widening gap already observed between LCAs in academia and industry practice [5]. To support immediate action, methodological developments should aim at striking a balance between improving accuracy and limiting additional complexity to current practice. New approaches need to be simple, allowing for a wider use both by academics and practitioners, as well as facilitating uncertainty assessment and sensitivity analyses [171]. With these criteria and the respective strengths of DLCA and GWP_{bio} in mind (Table 7), the authors argue that the GWP_{bio} approach is better adapted for the assessment of biogenic carbon in current building LCA practice. To implement it in current global warming impact assessment practice, the proposed workflow would be to (i) obtain the dynamic emission profiles of the studied biomaterial (see Section 4.2); (ii) calculate the radiative forcing, AGWP and AGTP curves using a programming script (see, for instance, [81,105,106]); (iii) obtain GWP_{bio} and GTP_{bio} dynamic characterization factors (DCF) for 20- and 100-year time horizons from the programmed script [54,78]; (iv) use a LCA software, for example the open source software OpenLCA, create new CF for the studied biomaterial in an existing LCIA method, and update its value with the desired GWP_{bio} and GTP_{bio} DCF; and (v) modify the process contribution tree of the studied biomaterial so that the biogenic carbon emissions attributed to it use the new CF. This would allow for the dynamic life cycle impact assessment of any biomaterial, or any material with a dynamic emission profile. However, the risk of errors and the complexity of the approach increase proportionally to the number of manually updated DCF.

Table 7. Synthesis of the DLCA and GWP_{bio} approaches and their respective advantages.

	DLCA	**GWP_{bio}**
Description	LCA framework	Emission metric
Initial Purpose	To solve inconsistency and time sensitivity issues in LCA	To assess the life impacts of regenerative biomass by integrating it with the global carbon cycle
LCI	Dynamic	Static—dynamic elements are included in the DCF
LCIA	Dynamic characterization factors, fixed endpoint	Dynamic characterization factors, fixed endpoint
Emission Metric	GWI_{inst}, GWI_{cum}; can be adapted to other metrics.	GWP_{bio}, GTP_{bio}; can be adapted to other metrics.
Sensitivity to TH	High	High
Advantages	Scales well for large amount of processes, if dynamic LCI data is available; Treats fossil and biogenic GHG emissions equally and simultaneously, using the same DCF.	Can be selectively applied to specific processes; Can be combined with other biogeophysical effects (e.g., albedo); Can be used within conventional LCA software; Might be useful for reporting biogenic carbon in EPD; Requires less data.
Potential Issues	Major LCI databases and LCA software do not currently support dynamic LCI; Using the DLCA framework to its full potential will only be possible after major DLCI data requirements are met.	Applying GWP_{bio} only to selected processes can introduce inconsistencies; Using it in conventional LCA software might become tedious for large amount of processes (multiplication of unique DCF).

5. Limits of This Review

This critical review applied a subjective conceptual depth criterion to confine its scope, and then used a more systematic approach to ensure a thorough review of the literature. It does not claim to be fully comprehensive, but it reflects the current state of the literature on the climate change LCIA of biogenic carbon in attributional, process-based LCA.

Knowledge gaps remain before best practices can be established for the dynamic LCIA of biogenic carbon in building LCA. The influence of biogenic-carbon-related LCI aspects would require a review of its own; for example, the modelling of natural disturbances, indirect land-use change, soil carbon content, forest regrowth models (before or after harvest), and rotation length can all have important consequences on the results (see, for example, [38,94,96,104,172–174]). The same goes for displacement factors, for which there seems to be no established guidelines [175,176]. Uncertainty assessment is another key knowledge gap that was excluded from the scope of this review. Underlying uncertainties in natural biomass production models [60] and in biogenic carbon impact assessment methods must be addressed if LCA is to be relied on for decision- and policy-making. For example, the approximation of using metrics based on IRFs for distributed emission profiles in dynamic approaches should be evaluated. Although the choice of time horizon is the most important factor that determines the time-integrated IRF for CO_2 and AGWP, variations in pulse sizes, background atmospheric concentrations and carbon cycle-climate models also contribute to uncertainties [145]. The uncertainty linked with selectively applying GWP_{bio} to processes with highly dynamic emission profiles while using conventional metrics for other processes should be evaluated. This would confirm the extent and level of certainty to which GWP_{bio} can be used as a proxy for a full DLCA. A better assessment of the uncertainty of dynamic approaches would also be consistent with recent recommendations for a wider use of sensitivity and uncertainty analysis in building LCA [171,177].

6. Conclusions

Reducing the carbon footprint of the built environment is an important step to contribute to reaching short-, mid- and long-term global warming reduction targets. Combined with sustainable forest management strategies and substitution benefits, using more biomaterials such as harvested wood products in buildings could significantly contribute to climate change mitigation. However, selecting and promoting efficient solutions will require a better understanding of the life cycle global warming impacts of biogenic carbon. To help enhance current practice, this paper presents a critical review of biogenic carbon impact assessment methods, compares two main dynamic approaches, and identifies one that is well suited for the assessment of biogenic carbon in process-based, attributional building LCA.

The reviewed dynamic approaches were split into two categories: Approaches including the dynamics of biogenic carbon emissions and removals related to the forest (*F*), product (*P*) and substitution (*D*) pools in the LCI, but using static, fixed time horizon metrics (Category 3); and (2) approaches including the same DLCI elements, but using fixed endpoint, dynamic CF (DCF) (Category 4). To avoid inconsistencies in the LCIA and to facilitate comparison and benchmarking, Category 4 approaches are preferred. 58 articles totaling 20 Category 4 approaches were qualitatively compared, and two approaches were selected for their flexibility and for their considerable presence in the reviewed literature.

Two main dynamic approaches were compared, DLCA and GWP_{bio}. In cases where dynamic LCI data is available and for simpler LCAs where time information matters, DLCA provides a comprehensive framework. It should be used for its better consistency and equal treatment of all carbon fluxes. However, for more complex LCAs or when LCA resources (data, time) are constrained, GWP_{bio} can provide a simpler, reliable proxy for practitioners. Because of the inherent complexity of building LCAs, the GWP_{bio} approach is suggested to practitioners for the application to biogenic carbon LCIA in building LCA. A typical workflow to include GWP_{bio} DCF in building LCA practice was presented. Further research should address more complex aspects of the GWP_{bio} approach, for instance the treatment of allocation for multi-output processes and the modelling of biogenic carbon emissions including multiple GHG. To increase the approach's usefulness, a thorough assessment of its associated uncertainty would also be highly relevant.

The results of this critical review will help LCA practitioners choose a biogenic carbon impact assessment method suited for their needs. By increasing awareness of dynamic approaches and GWP_{bio}, it aims to encourage a better assessment of the climate change mitigation potential of forest ecosystems, harvested wood products and timber buildings. This could contribute to shaping more efficient integrated solutions to maximize the climate change mitigation potential of sustainable forest management, storage in wood products and substitution. By simultaneously increasing GHG mitigation and removals, this would help bridging both of the gaps identified by Gasser et al. [29], and help the United Nations reach the decarbonization goals they set under the Paris Agreement in 2016.

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