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WOOD AND OTHER RENEWABLE RESOURCES

Balancing the green carbon cycle — Biogenic carbon within life cycle assessment

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Abstract

Purpose Accurate assessment of environmental impacts is key to the successful implementation of sustainability policies in both the short and long term. A critical component, particularly in assessing areas like the developing bioeconomy, is the handling of carbon of biogenic origin. This paper examines current methodologies and their ability to assess biogenic carbon.

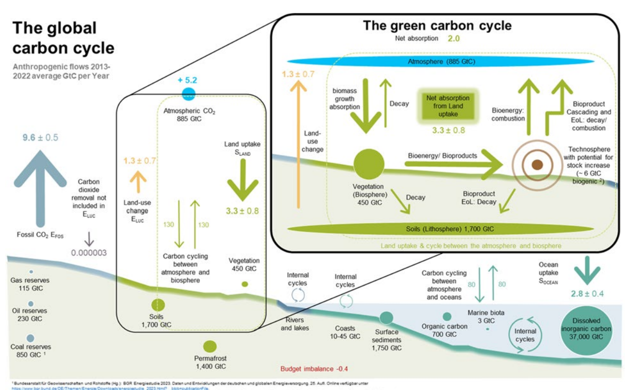
Methods We quantitatively evaluate different biogenic carbon accounting methodologies using our new conceptual framework — the green carbon cycle (GCC). The GCC is a subcycle of the global carbon cycle and supports understanding the accuracy of methods in capturing all essential biogenic carbon flows. Applying the GCC, we examine the advantages and disadvantages of dynamic LCA, GWPbio, and the − 1/ + 1 method under identical assumptions in four examples.

Results and discussion The methods reveal both differences and similarities, depending on the specific application. When focusing on growth cycles only, dynamic LCA and GWPbio deliver almost identical results for the assessment of biogenic carbon. However, when extending the view to the entire life cycle of a biomass-based facade cladding, dynamic LCA finds significantly lower impacts than GWP_{bio}, mainly due to the different assumptions concerning the timeframe from biomass growth until end of product life. Based on the distinct strengths and weaknesses of applying the GCC, we provide a decision matrix for practitioners to facilitate the right choice for each application.

Conclusion This paper enables researchers and practitioners to accurately assess biogenic carbon and to determine the best available approximation of the conditions in the GCC. It also identifies similarities and differences between the methods and shows how to overcome some of the identified weaknesses.

Graphical Abstract

(Adapted from Friedlingstein et al. (2023))



Keywords Biogenic carbon · Life cycle assessment · Dynamic life cycle assessment · Global warming · Carbon storage · Carbon cycle

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Extended author information available on the last page of the article

1 Introduction

It has been over 300 years since the Saxonian mining officer Hans Carl von Carlowitz (Carlowitz 1713) introduced the idea of managing a natural carbon cycle for the first time by demanding forestry practices where harvesting does not exceed regrowth. The concept of sustainability in forestry was born. Since then, this concept has become increasingly important (Kloepffer 2008). Nevertheless, humanity keeps overcharging the ability of natural systems to regenerate. Already, six out of nine overarching systems, defined as planetary boundaries, have been transgressed in the meantime (Richardson et al. 2023). Many measures are taken to tackle these problems that are subsumed within sustainable development (United Nations 2015). One proposed solution is the so-called bioeconomy. It describes — among other approaches — the utilization of biomass to replace fossil resources in the world's economy (Fröhling & Hiete 2020; Metic et al. 2022). While offering promising opportunities, bioeconomy is not an end in itself. Not every aspect of the concept is more sustainable than the current practice (Metic et al. 2022). Therefore, bioeconomy has already earned much criticism (Lewandowski 2018; Brandão et al. 2024).

Thus, it must be ensured that biogenic resource use complies with sustainability goals. This has to be determined by a respective assessment, e.g., life cycle sustainability assessment (LCSA) (Fröhling & Hiete 2020). In the context of the bioeconomy, the assessment of biomass and the induced effects are especially relevant to sustainability performance. One of the most discussed aspects is how to assess carbon originating from biological sources, so-called biogenic carbon (IPCC 2019), and its effect on climate change when emitted into the atmosphere (Pawelzik et al. 2013). There are even projects specifically dedicated to creating and setting standards for assessing biogenic carbon within LCSAs (life cycle initiative, 2024; Hamelin et al. 2024). Chemically, carbon-based greenhouse gases (cGHG) such as CO_2 and methane originating from biogenic sources are identical to cGHG released from fossil deposits, which means that, in the first step, both affect climate change similarly. However, their overall effect is different when considering the whole life cycle. This is because, in the case of biogenic carbon, it is circulated through several other corresponding processes linked to the emission of cGHG (e.g., sequestration through growth or formation of soil organic matter). For better differentiation, we refer to this subsystem of the global carbon cycle as the "green carbon cycle" (GCC). Brandão et al. (2019) found 15 different assessment methods dealing with the impact of biogenic carbon on climate change. Cardellini et al. (2018) compared different assessment methods quantitatively and found significant differences in the results. While some biogenic carbon assessment methods attested the analyzed systems a long-term carbon storage function, other methods resulted in long-term net emissions. Together with inconsistent regulatory specifications (e.g., within EU RED for advanced biofuels), extreme impacts on sustainability results are seen. Nevertheless, no consensus has been reached on which method should be used to assess the impact of biogenic carbon and adequately represent the real conditions depicted in the GCC (Life Cycle Initiative, 2024; Hamelin et al. 2024).

In this article, we want to provide guidance in bioeconomy, LCA research, and practice for assessing the global warming effects of biogenic carbon. Therefore, we will discuss the effects of biogenic carbon on the GCC and evaluate whether the selected assessment methods can depict reality properly. We analyze the properties of the approaches further and provide a detailed decision support matrix on when to use which method. Concludingly, we identify critical research gaps.

2 Materials and methods

This paper builds upon a literature review exploring the currently available and commonly used biogenic carbon accounting methods. Subsequently, we provide four examples to showcase how the existing methods for biogenic carbon accounting differ in them. For a better understanding of the different methods, we start with the current understanding of the global carbon cycle.

Climate change, as such, is a consequence of changes in the global carbon cycle. By releasing significant amounts of cGHG into the atmosphere, human activities are the main driver for climate change (Schaub und Turek 2016). This applies to both fossil and biogenic carbon stocks. The type of cGHG (fossil or biogenic origin) itself does not influence the impact of the gases in the atmosphere. Nevertheless, the corresponding systems within the global carbon cycle determine the overall climate impact of the emissions over the review period by the different retention times in the atmosphere. Therefore, it is not sufficient in climate change assessment to only look into the immediate impact of cGHG; a closer look into the global carbon cycle is necessary. Similar to Carlowitz's description, the interaction between the duration of sequestering and the release of carbon is important. In our work, we focus on the role of CO_2 as cGHG in biogenic carbon assessment methods. We acknowledge that other cGHG, such as methane, also have significant impacts. Nevertheless, many methods and tools in biogenic carbon assessment (e.g., the Yasso model (Liski et al. 2005)) only account for CO_2. The following introduces the current understanding of the global carbon cycle and describes biogenic carbon assessment methods.

2.1 Carbon cycle

As described by Friedlingstein et al. (2023) or Kirschbaum et al. (2024), the global carbon cycle is one of several natural bio-chemical cycles occurring on Earth. In this global carbon cycle, several stocks like vegetation, soils, permafrost, the atmosphere, oceans, or fossil reservoirs underlie a set of natural and anthropogenic processes that lead to flows between the stocks. The overall cycle is described in the Graphical abstract. Especially anthropogenic processes like the combustion of fossil fuels or changes in land use that lead to a change in the natural interaction between the stocks and flows. The increase in the concentration of, e.g., carbon dioxide in the atmosphere is a main driver of man-made climate change (IPCC 2023). In the last decade, 9.6 Gt of carbon per year have been mobilized from the fossil reserves, and 1.3 Gt resulted from land-use change on average. Additional carbon stock in the atmosphere of 5.2 Gt remained after vegetation and oceans removed parts of the emissions (Friedlingstein et al. 2023). The main issue about this additional carbon stock mobilized through anthropogenic processes (i.e., from fossil resources or soils) is the rising radiative forcing of the atmosphere, i.e., an increasing greenhouse effect.

Flows decreasing the amount of cGHG in the atmosphere are a possible lever for climate mitigation. Mengis et al. (2023) identify the sequestration of CO_2 in the ocean and its ecosystems as an important contribution. However, the largest carbon dioxide net uptake occurs through plant growth in terrestrial systems, with around 3.3 Gt of carbon per year (see Graphical abstract). Consequently, many authors have identified vegetation and the use of products from biomass as promising measures. For instance, Watari et al. (2024) investigate the impact of the usage of timber for buildings on the carbon cycle in the case of Japanese housing. Thereby, they take up the idea of combating climate change by building up another carbon stock in the form of buildings and infrastructure made from biomass, as described by Churkina et al. (2020). Besides this, vegetation has other effects on climate change, for example, through the change of surface albedo (Kirschbaum et al. 2024) or carbon releases from soils (Schmidt et al. 2015; Wei et al. 2024). Pongratz et al. (2021) specify the impacts of land use and management on climate change more closely and emphasize the need for sustainable use of biomass (Carlowitz, 1713). Transferred to the GCC, "sustainable use" in terms of climate change means that the positive effect of the absorption via biomass growth must be at least equal to the negative effect of the cGHG released via decay or combustion. Sustainable use of biogenic resources thus requires at least an equalized balance between the dynamic effects of carbon release and uptake.

2.2 Biogenic carbon assessment methods

In the current literature, which we analyzed in a literature review, multiple approaches of varying complexities exist to treat biogenic carbon (Hoxha et al. 2020; Cucurachi et al. 2022). The methodology and detailed results of the literature

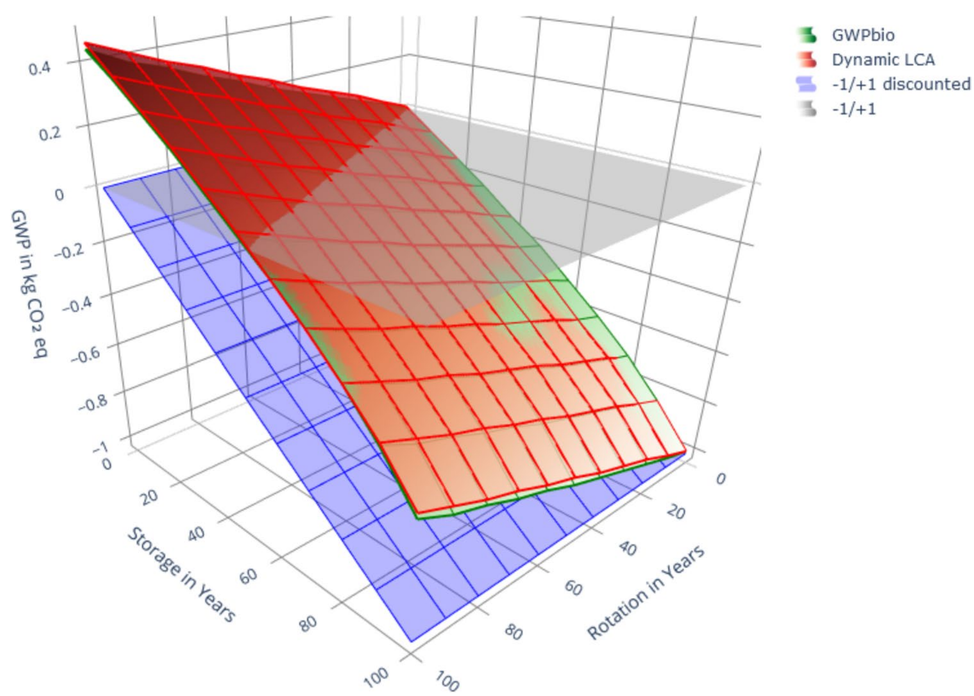

Fig. 1 Results of example 1 along the storage and rotation period dimensions in years and *GWP* impact in CO_2eq. GWP_{bio} taken from Guest et al. (2013a). Dynamic LCA and − 1/+ 1 (discounted) based on own calculations

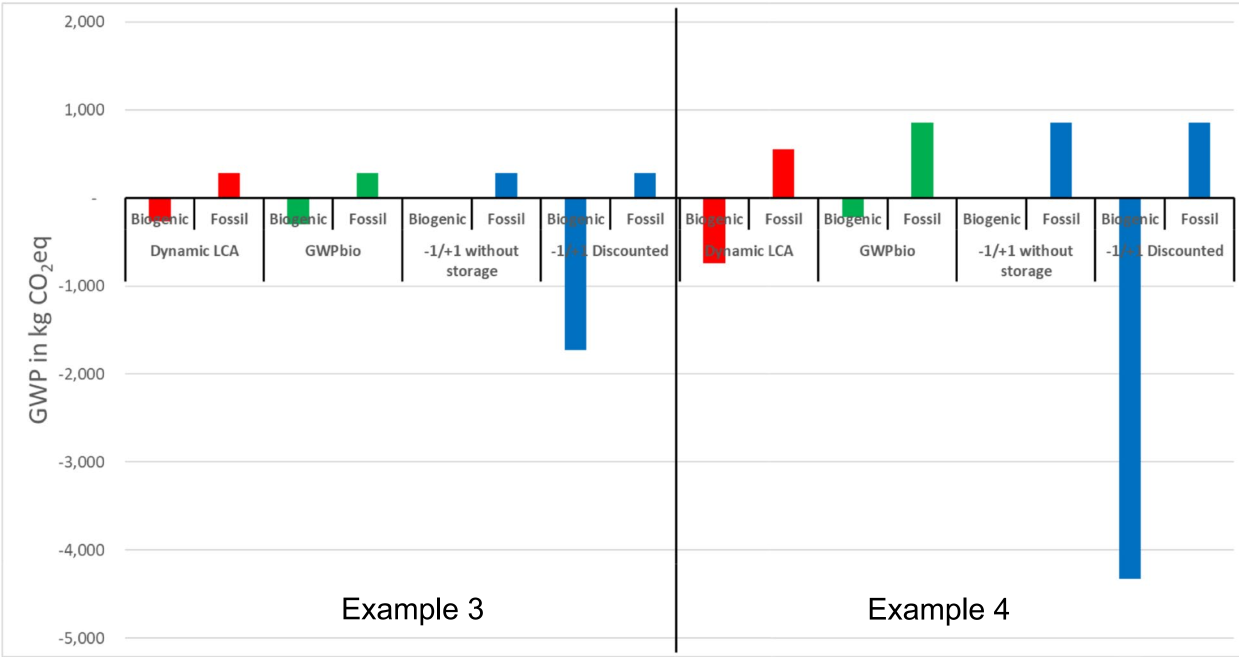

Fig. 2 Results for examples 3 and 4 in kg CO_2eq. Example 3 is the life cycle of one larch wood cladding, and example 4 is the life cycle of larch wood cladding over the whole life cycle of a building. Both examples have a 100-year time horizon

review are found in the supporting information (SI) chapter 1. Figures 1 and 2 of the SI show the general method for the structured literature review and the identified papers for inclusion.

The most common methods are either to ignore the impact of biogenic carbon dioxide (0/0 approach) or to trace all biogenic carbon flows over the life cycle of an observed system, which is the – 1/+ 1 method. This approach is widely embraced by official standards and guidelines such as the ILCD handbook, PAS 2050, EN- 16485, or ISO-14067 (Hoxha et al. 2020; Cucurachi et al. 2022; Pscherer & Krommes 2024)). In the – 1/+ 1 method all biogenic carbon flows occurring in the GCC are added to the life cycle inventory with an equivalent value to fossil carbon. All uptakes are fully counted as negative emissions (e.g. – 1) of CO_2eq and all emissions into the atmosphere are fully counted as positive (e.g. + 1), hence the designation as – 1/+ 1 Method (JRC, 2010).

Sequestration of CO_2 in biomass is typically placed at the beginning of a product life cycle, and all stored carbon is emitted at the end of life. Storage effects can be included optionally by different forms of discounting, with JRC (2010); however, noting that since any emission will ultimately exert its full radiative effect, even if delayed, storage effects should only be considered if explicitly part of the goal of a study and should be documented separately. If discounting is applied, it can be argued that the approach should no longer be considered as a – 1/+ 1 Method, given that the + 1 side is discounted. However, since the guiding literature recommends such a linear discounting approach in conjunction with the – 1/+ 1 Method, the terminology "– 1/+ 1" is retained in this paper as "– 1/+ 1 Discounted" Method, in order to show the impact on the final results of the undiscounted – 1/+ 1 Method.

Beyond – 1/+ 1, two main advanced methods exist: the GWP_{bio} approach and the dynamic LCA approach. In our literature review with 96 analyzed studies dealing with more advanced biogenic carbon methods, we find 39 covering GWP_{bio} and 38 dynamic LCA, showing the strong prevalence of these methods (see SI Figs. 3 and 4). A detailed literature analysis and a breakdown of both approaches, including the equations to perform them, are found in the "Materials and methods" section and chapter 1 of the SI.

The concept of GWP_{bio} was first developed by Cherubini et al. (2011), who proposed a characterization factor specific to biogenic CO_2, considering the temporal delay between harvest and regrowth of biomass.

In the GCC, 3.3 Gt of carbon is taken up annually, covering the possible emissions of one product's life cycle. Nevertheless, the 3.3 Gt per year is the total uptake covering all ecosystems on Earth. Consequently, when assessing a single product, it is still necessary to consider the specific growth parameters of the used biomass so as not to double-count sequestration in the summary of many small-scale product-specific LCAs. Therefore, in Cherubini's approach, carbon sequestration occurs over time and may take several years for many biomass sources, such as wood. In the GWP_{bio} concept, this growth is placed after biomass harvest as regrowth.

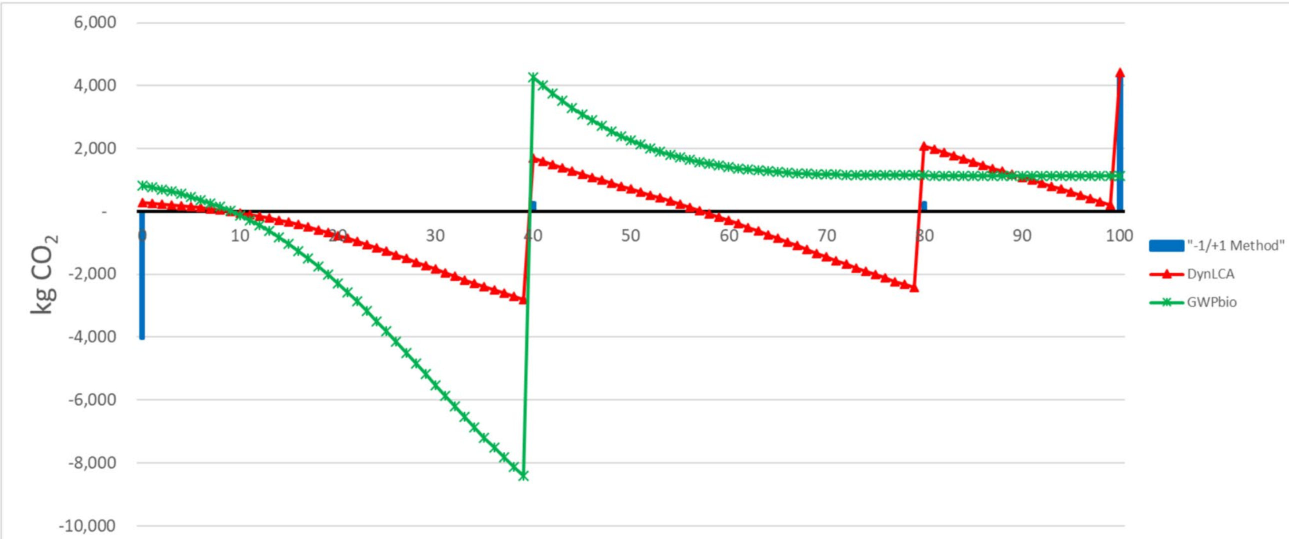

Fig. 3 Cumulative emissions in kg CO_2eq for calculation example 4 as the life cycle of larch wood cladding over the whole life cycle of a building with a time horizon of 100 years

It is assumed that harvest alters the biogenic carbon cycle by inducing additional regrowth and, thus, sequestration. This additional sequestration is included in the calculation of the GWP_{bio} characterization factor.

The calculation of GWP_{bio} follows a modification of the standard formula for GWP_{CO2} shown in Eq. (1). Using the function of the additional growth caused by the harvest $g(t)$, a convolution with the atmospheric decay function $y(t)$ of CO_2 is formed, resulting in Eq. (2).

$$GWP_{CO_2}(TH) = \frac{AGWP_{CO_2}(TH)}{AGWP_{CO_2}(TH)} = \frac{C_0 * \int_0^{TH} \alpha_{CO_2} \times y(t)dt}{C_0 * \int_0^{TH} \alpha_{CO_2} \times y(t)dt} \quad (1)$$

$$GWP_{bio}(TH) = \frac{AGWP_{bio}(TH)}{AGWP_{CO_2}(TH)} = \frac{C_0 \times \int_0^{TH} \alpha_{CO_2} \times \left(y(t) - \int_0^{TH} g(t\prime)y(t - t\prime)dt\prime \right) dt}{C_0 \times \int_0^{TH} \alpha_{CO_2} \times y(t)dt} \quad (2)$$

With the convolution of $g(t)$ and $y(t)$, the additional removal of CO_2 from the atmosphere due to additional growth is included in the GWP_{bio} factor. C_0 describes the initial emission pulse; TH is the chosen time horizon; and α_{CO2} is the radiative efficiency of CO_2.

The atmospheric decay function $y(t)$ of CO_2 is described as:

$$y(t) = y_0 + \sum_{i=1}^{3} y_i \times e^{-\frac{t}{\tau_i}} \quad (3)$$

The parameters for y_i and τ_i are set as $y_0 = 0.2173$, $y_1 = 0.2240$, $y_2 = 0.2824$, $y_3 = 0.2763$, and $\tau_1 = 394.4$, $\tau_2 = 36.54$, and $\tau_3 = 4.304$ (Myhre et al. 2013).

Cherubini et al. (2011) modeled the growth $g(t)$ as a function of the rotation period of the biomass, with μ as half the rotation period and σ as a quarter of the rotation period.

$$g(t) = \frac{1}{\sqrt{2\pi \times \sigma^2}} \times e^{-(t-\mu)^2/2\sigma^2} \quad (4)$$

This function for the regrowth of biomass based on the rotation period is also adopted in this study.

Guest et al. (2013a) expanded the GWP_{bio} to include the effect of delayed emissions and storage, resulting in GWP_{bio} factors specific to the rotation period and storage duration.

Dynamic LCA was originally proposed by Levasseur et al. (2010) to resolve temporal inconsistencies in the LCA methodology (Shimako et al. 2018). Levasseur et al. (2013) then applied the concept to biogenic carbon. Ventura (2022) later proposed a refined version of dynamic LCA tackling time horizon issues.

In principle, dynamic LCA treats biogenic and fossil carbon emissions identically and does not differentiate between them. However, this method allows for the time-dependent aspects of biomass (re)growth to be considered.

In dynamic LCA, a temporally explicit LCI is constructed by recording all emissions and uptakes of GHG occurring each year over the whole observed time horizon. This LCI for biogenic carbon in this study is calculated with the growth function g(t), as shown in Eq. (4). As Levasseur et al. (2013) described, these annual GHGs are then assessed using dynamic characterization factors (*DCF*s), which reflect the impact of one emission *i* that occurred *t* years before. The sum of all emissions up to year *t* multiplied by the $DCF(t)$ results in the instantaneous global warming impact GWI_{inst} of year t, as shown in Eq. (5).

$$DCF_i(t) = \int_{t-1}^{t} \alpha_i \times y_i(t) \tag{5}$$

$$GWI_{inst}(t) = \sum_{j=0}^{t} C_i(j) \times DCF_i(t-j) \tag{6}$$

The sum of all GWI_{inst} up to year t then results in the cumulative global warming impact $GWI_{cum}(t)$.

$$GWI_{cum}(t) = \sum_{j=0}^{t} GWI_{inst}(j) \tag{7}$$

By dividing $GWI_{cum}(t)$ of a chosen TH by the $AGWP_i$ of GHG_i of the same TH, a GWP result comparable to the result of static methods can be calculated.

$$GWP(TH) = \frac{GWI_{cum}(TH)}{AGWP_{CO_2}(TH)} \tag{8}$$

As with the GWP_{bio} method, biomass harvest is assumed to induce additional change in the biogenic carbon cycle by inducing growth. In dynamic LCA, this growth can be placed before or after the harvest event (Hoxha et al. 2020). Hence, with its temporal differentiation dynamic LCA is best suited to model the GCC properly.

2.3 Example applications of assessment methods

A common conclusion in the current literature on the assessment of biogenic carbon is that the results of an analysis are highly dependent on the choice of method (Brandão et al. 2019; Olofsson 2021). We test this assertion with four examples using identical assumptions to reveal what differences in results arise from the actual choice of method and what do from the assumptions combined with these methods. The examples highlight the method's commonalities, differences, strengths, and weaknesses while using a realistic product as a case. Through this, we aim to provide further guidance on the choice of methods and their suitability to account for biogenic carbon in LCA by shedding light on how the three methods' outside assumptions and inherent conceptual attributes shape their results.

The key assumptions are (1) the same growth function based on a normal distribution and defined by the rotation period of the biomass, shown in Eq. (4), (2) an identical placement of growth in the life cycle, and (3) identical time horizons. Further, we select GWP_{100} as a common characterization model (IPCC 2023). There are several other metrics for climate change, like GTP or GMTC, which have advantages over GWP in certain applications. Nevertheless, they require additional assumptions, e.g., specific climate goals or time targets, as discussed by Tiruta-Barna (2021). Hence, we decided to use the wide-spread method GWP_{100} to minimize the impact of additional assumptions on our results.

The GWP_{bio} factors, as found in Guest et al. (2013a), were directly taken for the example calculation. Since GWP_{bio} demands placing growth as regrowth after the harvest event for the convolution, the same placement as regrowth and the same growth function were used for dynamic LCA as well. The chosen time horizon is 100 years, fitting with GWP_{100}. For the – 1/+ 1 Method, results are calculated without the optional storage effect, reported separately under the term "– 1/+ 1 discounted" following JRC (2010). This term is used to show that the discounting is optional but connected to the – 1/+ 1 Method.

Example 1 seeks to test if differences arise from each method's basic assumptions and mathematical structure when calculating emission factors from primary biomass. To do so, the case is kept simple. The dynamic LCA method and the – 1/+ 1 Method are applied to only 1 kg of biogenic CO_2 emission, which originates from primary biomass of different rotation periods and is emitted after different storage times from 0 to 100 years in 10-year steps. All biogenic carbon is assumed to be emitted at the end of the storage period in a pulse emission. The rotation periods and storage times are chosen to match the ones for the reported GWP_{bio} factors from Guest et al. (2013a). This example further tests if the dynamic LCA method can, in principle, recreate GWP_{bio} factors.

Example 2 investigates how each method can be applied in the case of secondary biomass. This example considers 1 kg of biogenic carbon from harvest residues from spruce wood with a rotation period of 80 years. Different storage times and the assumption of emission at the end of the storage period are applied, as shown in example 1. This example also showcases the flexibility of each method to be applied to different biomass cases. Harvest residues are a by-product of forestry operations, which can either be left in the forest to decay or be collected for use. However, removing residues does not necessarily cause regrowth (Helmisaari et al. 2011). Guest et al. (2013b) consider the role of forest residues for GWP_{bio} factors but argue the GWP_{bio} factors for collected residues should be the same as for primary biomass. In practice, published GWP_{bio} factors are applied by several studies, even when the explicit counterfactual to the collection of residues is their decay on site (Havukainen et al. 2018; Olofsson 2021; Pfau et al. 2019). Dynamic LCA allows for a more flexible inclusion of other counterfactuals and consequences other than regrowth. Since the alternative fate of the harvest residues is decay in the forest, their use avoids this decay. The avoided decay can be included instead of a growth function for dynamic LCA. For this purpose, we use the Yasso model (Liski et al. 2005) to simulate wood decay equivalent to 1 kg of biogenic carbon. Yasso delivers the annual emissions caused by such a decay, which are included in the dynamic LCA calculation in place of a growth function by multiplying them with − 1 to represent that the use of the harvest residues avoids them.

The − 1/+ 1 Method finally treats biogenic emissions of secondary and primary biomass identically.

The third example seeks to test the implementation of each method for a real-world wood product under identical assumptions and with only one product life cycle considered. Similar to example 1, this example highlights potential differences due to each method's intrinsic assumptions and mathematical structure. The functional unit for this example is "providing one.

wood cladding for a one-family house with 242 m^2 of surface area made from larch wood." With an average thickness of 2 cm and a density of 487 kg/m^3 for larch (Pretzsch 2019), this is equivalent to 2357 kg of wood with an assumed carbon content of 50%. The rotation period of larch is 60 years, and the storage period for wood cladding is 40 years. The fossil emissions of 286 kg of CO_2eq due to harvest and production are taken from Russwood (2022) and are assumed to occur in the first year. For the end of life, it is assumed that the wood cladding will be fully burned and all biogenic carbon emitted into the atmosphere. The life cycle is considered cradle to grave.

Example 4 finally seeks to extend example 3 by considering not just one life cycle of wood cladding but wood cladding over the full life cycle of a building.

The functional unit of this example is thus expanded to "providing cladding over the whole 100-year life span of the house." Since the life span of one wood cladding is 40 years, this addition requires a replacement of the wood cladding after 40 and after 80 years. For the cladding installed after 80 years, a storage period of only 20 years is assumed due to the end of life of the whole house after 100 years. The life span for this example is chosen intentionally so that the third cladding for the house is removed before its full lifetime is reached to further test how each method handles such cases, which are common in LCAs for buildings.

In combination, these four examples seek to illustrate the analyzed methods' performance under different conditions to reveal strengths and weaknesses and how each method handles key questions and assumptions.

3 Results

This section presents the results of the four examples we described. The results of the first example calculation compare the GWP_{100} of 1 kg biogenic CO_2 depending on rotation period and storage time. The second example illustrates the assessment of harvest residues, and the third and fourth example assesses the practical case of wooden larch cladding with different lifetimes (40 and 100 years). The detailed results for our examples can be found in the SI chapter 2.

3.1 Results for example 1 and example 2

Figure 1 shows the results for all three methods in example 1. In order to represent the large number of results, with each combination of storage time and rotation period leading to different results, a graphical representation is chosen. For the − 1/+ 1 Method, all results equal no impact since the same amount of biogenic carbon is released as was taken up before. The − 1/+ 1 discounted shows the effect of discounting with storage time, but since this approach does not take into account growth over time, the rotation period has no impact on the results.

The results in absolute values are found in the SI Tables 1 to 3.

The dynamic LCA method produces results similar to those of the GWP_{bio} method. On average, the results of the two methods differ by 0.01 kg CO_2eq.

Only the rotation period of 1 year produces strongly diverging results and shows a very large impact for dynamic LCA, while the GWP_{bio} factors are small. This difference results from using the growth curve as a function of the rotation period, which for rotation periods smaller than 1.5 years no longer do model the full regrowth. Entering a rotation period of 1 year only covers a regrowth of up to 44%, while at 1.5 years, full regrowth is modeled again. Cherubini et al. (2011) report that the integration of the convolution is

Table 1 Results of example 2 in $kgCO_2$eq from spruce harvest residues with a rotation period of 80 years considering a time horizon of 100 years

Storage time	0	10	20	30	40	50	60	70	80	90	100
Dynamic LCA	0.80	0.72	0.64	0.55	0.47	0.37	0.28	0.18	0.07	− 0.05	− 0.20
GWP_{bio}	0.34	0.26	0.18	0.10	0.02	− 0.07	− 0.17	− 0.27	− 0.38	− 0.50	− 0.66
− 1/+ 1 Method	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
− 1/+ 1 discounted	0.00	− 0.10	− 0.20	− 0.30	− 0.40	− 0.50	− 0.60	− 0.70	− 0.80	− 0.90	− 1.00

solved by numerical approximation, which may explain why this breakdown of the growth function at a rotation period of 1 year was not noticed.

Generally, for both dynamic LCA and GWP_{bio}, a lower rotation period, which indicates faster growth, leads to lower GWP. Longer storage periods show the same effect. Thus, the lowest impact is achieved with biogenic carbon from short-rotating biomass and long-lived products.

The results of example 2 are summarized in Table 1. Here, the difference between the GWP_{bio} and dynamic LCA approaches is considerably larger. This shows the significant impact of choosing a different growth, or in this case, an inverted decay function instead of a growth function.

Overall, the impacts of dynamic LCA are consistently larger compared to the GWP_{bio} results. This can be explained by the difference between the avoided decay curve used for dynamic LCA and the growth curve used for GWP_{bio}. Collecting and using harvest residues means that the decay, which would otherwise occur over time, is concentrated into a pulse emission at the end of the storage period. Thus, emissions that would otherwise be delayed are occurring earlier, while emissions from early in the decay are delayed by the storage period. In the GWP_{bio} approach, decay does not play the same role, and the collected harvest residues are treated the same as primary biomass and as if they are causing additional growth.

The − 1/+ 1 Method ultimately shows no impact for secondary biomass due to its assumption that all biogenic carbon contained in it was first absorbed and then later released, which, in sum, results in no impact. The discounting method makes no difference between primary and secondary biomass, as only the storage time is considered a factor in linear discounting.

3.2 Results for examples 3 and 4

For the third example, dynamic LCA and GWP_{bio} again deliver similar results, while the − 1/+ 1 Method diverges strongly. As shown in Fig. 2, GWP_{bio} results in low negative GWP_{100}, while dynamic LCA has a low positive value. The numerical values of the results in examples 3 and 4 are found in the SI Table 4. The absolute difference between both methods of 39.4 kg CO_2eq is the same as in the first example when linearly scaled with the amount of biogenic CO_2 occurring in the third example. For the − 1/+ 1 Method, the results are identical to those of fossil emissions, as the same amount of biogenic carbon is first considered a negative emission and then a positive emission at the end of life. The results show a strong negative impact if storage is considered with the − 1/+ 1 discounted.

Only in the fourth example do all four methods noticeably diverge, with lower impacts calculated by dynamic LCA than the GWP_{bio} method. This arises from the conceptual difference between the static LCA and the dynamic LCA approach, which can be seen in Fig. 3. Dynamic LCA integrates the impacts of an emission from the point of its emission to the end of the chosen time horizon of the analysis. Impacts occurring later and thus closer to the end of the time horizon become truncated. Only the part of the impacts within the time horizon is considered. Meanwhile, in GWP_{bio}, the full impact of this emission is counted, regardless of when it occurs. As shown in Fig. 3, the emissions are essentially treated as if they happen simultaneously, and their effects are considered to be fully without truncation.

For this reason, the fossil emissions are also lower in the dynamic LCA approach. As fossil emissions for producing the replacement cladding happen later in the life cycle, at 40 and 80 years, their impacts are truncated, while in the static approaches, they remain the same. In the second example calculation, these truncation effects do not impact the results because all fossil emissions and only one regrowth starting at the beginning of the life cycle occur.

The − 1/+ 1 Method, meanwhile, treats all biogenic sequestration to occur at the start and all biogenic emissions at the end of the time horizon. This creates strong spikes at the beginning and end. Suppose no storage is considered. These even out to 0. If storage is considered, a large negative effect is created. Fossil emissions can be traced to when they occur, but the timing does not affect their impact. Thus, the − 1/+ 1 Method considers emissions conceptually differently from dynamic LCA or GWP_{bio}, leading to different results.

4 Discussion

In the following, we discuss the results of applying the analyzed methods to the four examples. Therefore, we classify the results in the context of our conceptual framework and evaluate the accuracy of the assessment methods. Finally, we derive a condensed decision support matrix to help practitioners choose the right method for their application.

4.1 Similarities and differences of the analyzed methods

Examples 1 and 3 show that dynamic LCA and GWP_{bio} produce largely similar results if only one harvest event at the beginning of the life cycle is considered. In the first example, the GWP_{bio} method of incorporating the dynamic element of biomass regrowth into a static GWP_{bio} factor is equivalent to treating the regrowth with dynamic LCA. Both methods do not differ if the same regrowth function is used as a basis. However, if the regrowth starts later in the life cycle or secondary harvest events (e.g., for replacing a bio-based product) occur, as shown in example 4. The methods diverge due to the conceptual difference between static and dynamic approaches.

GWP_{bio}, despite introducing the dynamic element of regrowth into LCA, does this in the form of a static factor, which is precalculated and applied to all biogenic emissions in the same way, no matter when an emission occurs.

Dynamic LCA, however, treats emissions differently depending on when they occur in the life cycle. Thus, both fossil and biogenic emissions occurring in year 1 have a higher respective impact than the same emissions occurring in year 99. This causes both methods to diverge significantly as GWP_{bio} fits into the overall static model of traditional LCA, while dynamic LCA is entirely non-static.

However, if applied as in example 1 or 3, where the biogenic emission occurs, and regrowth starts at the beginning of the life cycle, the difference between dynamic and static does not impact the results. This makes it possible to apply dynamic LCA exclusively to biogenic carbon under a study's given conditions (regrowth time, storage period, etc.) and calculate a static GWP_{bio} mathematically in a far simpler way.

In that context, we show that all four methods analyzed are not perfect for modeling real-life conditions in the GCC. The − 1/+ 1 method does not account for temporal aspects at all and is, therefore, only a rudimentary model of the GCC. GWP_{bio} is more advanced and allows, to some extent, to incorporate the temporal distribution of events within the life cycle of a product. Hence, it delivers an improved understanding of the conditions in the GCC, giving a complete assessment of the impacts of biogenic carbon. Dynamic LCA is most capable of simulating real-life conditions in an LCI model. Nevertheless, the truncation of impacts due to the methodological assumptions concerning the time horizon within dynamic LCA leads, in some cases (e.g., example 4), to the partial neglect of impacts.

Strongly different results are finally seen in example 2. When secondary biomass is concerned, published GWP_{bio} factors and the − 1/+ 1 method treat this biomass as identical to primary biomass. Including avoided decay instead of regrowth is not readily available with GWP_{bio} as this would require a mathematically difficult implementation of a function for the avoided decay instead of the growth function $g(t)$ in Eq. (2). Dynamic LCA, on the other hand, allows for a far more straightforward combination with other tools, such as Yasso in the case of decay, showing the greater flexibility and ease of use of this approach, especially for secondary biomass, where different counterfactuals and consequences other than regrowth are important to consider.

4.2 Challenges and guidance for LCA practice

The choice and implementation of these methods in practice pose several challenges and questions to practitioners. These are addressed in the following paragraphs to guide practitioners on including biogenic carbon in LCA.

4.2.1 System boundaries

When considering biogenic carbon, choosing the system boundaries is especially critical. Biogenic carbon being sequestered, stored, and released in different life cycle stages, as seen in Fig. 3, makes it necessary to consider the full cradle-to-grave scope. The GWP_{bio} method inherently includes the end of life of a product in calculating its biogenic emission factors. Thus, if a study plans to use GWP_{bio}, a cradle-to-grave system boundary should be chosen to ensure consistency.

Dynamic LCA and the − 1/+ 1 method allow consistency with any chosen system boundary. Nevertheless, for these methods, the choice of the system boundaries poses an even greater potential pitfall. The − 1/+ 1 method considers the full sequestration at the start of the life cycle. If only cradle-to-gate is considered and the end of life is not analyzed, then no re-emission of sequestered carbon is accounted for. In this case, the method turns into a − 1/0 method and skews the result strongly towards lower impacts (Petrović et al. 2023). This may lead to false conclusions, especially when results are used by stakeholders who compare them to the impacts of other options.

Similarly, dynamic LCA considers the emission at the end of life, while the growth may be placed after or before harvest. If pre-growth is chosen, a cradle-to-gate system boundary may lead to the same bias as with the − 1/+ 1 method, while placing the growth after harvest may lead to parts of the regrowth being cut off. In their analysis, Hoxha et al. (2020) showed the effect of choosing pre-growth or re-growth perspectives for a full life cycle. Their results also show how a cradle-to-gate system boundary may truncate impacts.

Thus, it is recommended to always at least consider the beginning and end of the life cycle of products containing significant amounts of biogenic carbon. The end of life must be included as it is the point of emission of any stored carbon and a key point in the life cycle.

4.2.2 Modelling of growth

Growth modeling is the key factor for dynamic LCA and GWP_{bio} and must be considered carefully. GWP_{bio}, due to the way it is calculated, assumes only regrowth, while for dynamic LCA, the growth can be modeled as occurring before or after harvest. The choice of where to place the growth in the life cycle can influence results significantly (Hoxha et al. 2020) and is described as an unanswered question ("chicken and egg dilemma") (Hawkins et al. 2021). However, arguments for modeling regrowth appear stronger, and this perspective is more appropriate when considering the overall LCA methodology.

Hoxha et al. (2020) point out that a forward-looking approach should be preferred from a sustainability point of view to stimulate future growth. Matuštík and Kočí (2022) argue that regrowth should be considered as trees are always replanted to replace previously cut ones, but going back through time, the first felled trees of a forest were naturally grown, and thus the forest activity causes a chain of regrowth. Hawkins et al. (2021) argue that past growth has already occurred and is unaffected by any current choice, while future growth changes based on whether to harvest and replant. This also includes new afforestation, which can only occur in the future.

A further weakness in current studies of biogenic carbon in LCA is the use of simplistic growth functions. Cherubini et al. (2011) use a simple normal distribution as a growth curve for their GWP factors, while even more advanced approaches, as shown by Holtsmark (2015), rely on growth equations, expansion factors, and linear decay for deadwood. More advanced methods for estimating biomass growth, especially under different management and harvesting schemes other than clear-cut, should be considered in future studies to refine impact factors for biogenic carbon.

As shown in this study, however, it is possible to generate static GWP_{bio} factors using dynamic LCA. In example 1, dynamic LCA was applied to the same growth function that GWP_{bio} is based on, with the same assumptions on growth placement and storage times, and to only 1 kg of biogenic CO_2, resulting in nearly identical GWP_{100} factors. The difference between the two methods may only stem from rounding errors and the approximation used by Cherubini et al. (2011). Thus, the more flexible method of dynamic LCA can be applied to calculate new static GWP_{bio} factors for cases not covered by the as-of-yet available factors or with a more closely fitting growth function for different biomass sources. This use of dynamic LCA specifically for generating biogenic emission factors remedies the weakness of inconsistency with static LCA and the weakness of GWP_{bio} of new factors being exceedingly difficult to calculate for more complex growth functions.

4.2.3 Implementation of different types of biomass

While most crops grow within one season or year regardless of species, the growth times of forests can differ greatly depending on species. For GWP_{bio}, published factors only range up to 100 years of rotation period, requiring new calculations for species with longer growth times, such as oak or beech. Similarly, an inventory considering these growth times has to be calculated for dynamic LCA. However, calculating new GWP_{bio} factors is considerably more complicated than the dynamic LCA method.

Another important factor of the type of biomass is whether a study focuses on primary biomass or residues and byproducts. The GWP_{bio} factors assume that the harvest of the biomass under study causes additional carbon sequestration with induced regrowth. However, collecting residues or by-products does not necessarily cause regrowth. On the contrary, removing residues may even lower long-term regrowth by removing nutrients (Helmisaari et al. 2011).

The question of which assumption is more realistic or correct depends on the perspective of the case. If harvest residues are seen as by-products of primary biomass, considering their avoided decay instead of a growth function may be more appropriate. Should the counterfactual be different, and the choice of using residues cause more or less harvest and thus more or less regrowth, the GWP_{bio} perspective remains valid. However, in such a case, it should be questioned if such biomass should be termed harvest residues or secondary biomass since these terms typically denote that the biomass in question is a by-product that occurs regardless of whether it is used.

As shown in example 2, to calculate GWP_{bio} factors or implement this in dynamic LCA, the inverse of the decay function of the residues should be used in place of a growth function. To obtain fitting annual inventories for woody biomass, models such as Yasso (Liski et al. 2005) are fitting. Its results are well-suited to be combined with dynamic LCA. The greater flexibility of dynamic LCA for combination with other tools and replacing the growth function with other dynamic inventories makes this method better suited for different types of biomass and considering other counterfactuals.

Furthermore, when considering primary biomass products, such as stem wood from forestry, it is recommended to consider the full impact of harvests on the biogenic carbon cycle. Guest et al. (2013b) expanded the GWP_{bio} concept to include harvest residues left to decay. Holtsmark (2015) developed the method further to the full living biomass, harvest residues, natural deadwood, and soil carbon through simple expansion factors and decay curves. A significant point made by Holtsmark (2015) is also to apply a non-harvest scenario as a counterfactual or baseline scenario to compare the change due to harvest and quantify these impacts. Their calculation resulted in considerably higher GWP_{bio}, but they also recommend further improvement, for example, by considering deadwood decay and soil carbon in more detail with Yasso. These studies show that considering a broader scope of biomass is important to accurately assess its climate impact.

4.3 Decision support matrix

In the following, we summarize the most important observations made in this study, as well as the strengths and weaknesses of the selected biogenic carbon assessment methods. Table 2 showcases how each method handles key questions and challenges and gives guidance for choosing a method.

We see the field of application for the − 1/+ 1 method, especially in annual crops, as it delivers similar results to the other methods due to the very low delay between harvest and growth, but with the least effort required. For assessing perennial biomass, using the two more comprehensive methods is favorable as they offer better adaptability to the specific case. When choosing a method for biogenic carbon, it should be considered if primary or secondary biomass is studied. The full scope of living and dead biomass and the impact of soil carbon should be considered. Since the implementation of GWP_{bio} becomes increasingly difficult under these more complex circumstances, dynamic LCA is recommended overall. The more flexible dynamic LCA method can generate GWP_{bio} factors consistent with the static nature of traditional LCA, avoiding a core issue of dynamic LCA for biogenic carbon assessment.

5 Conclusion

The methods discussed in this paper attempt to describe the impact of human activities on the GCC. Different approaches take different viewpoints and levels of detail when analyzing this impact and relationship. In many cases, the development of new approaches is a reaction to the shortcomings of a previous approach. Hence, the advantages of one approach often also describe the disadvantages of another and vice versa.

The − 1/+ 1 approach is a widely used approach that has entered many standards and legislative acts concerning environmental assessments. Therefore, it offers comparability over various studies, reports, and assessments. One reason for its spreading may be the easy application and consistency with current LCA modeling practices. Nevertheless, the shortcomings of the approach are apparent. It oversimplifies the interactions within the GCC by using a static approach and treating growth and emission to occur instantly. Time delays for slow growth are not taken into account. The typical placement of all growth at the beginning of the life cycle and all biogenic emissions at the end also opens up the possibility of a strong bias in results if a cradle-to-gate system boundary is chosen. If storage is considered for separate reporting, only a linear storage function without a distinction between different types of biomass is suggested by the guiding literature. However, other discounting curves could be applied.

GWP_{bio} and dynamic LCA are able to take into account different aspects of biomass, such as growth and storage times. GWP_{bio} offers characterization factors consistent with traditionally static LCA based on rotation period. When taken from the available literature, they are easy to implement. However, the complexity of calculating new GWP_{bio} factors specific to the needs of a study is very high. Published factors do not consider the full scope of biomass or the type of biomass (primary or secondary). Growth is inherently assumed to be regrowth and cannot be placed before harvest. This makes GWP_{bio} simple to use in basic cases but difficult and inflexible when applied more in-depth.

Dynamic LCA, on the other hand, is the most adaptable approach. While the basic implementation is more challenging, the implementation complexity does not increase much when using dynamic LCA for other or new cases. Secondary biomass, different placements of (re)growth, or species with specific growth curves can be integrated comparatively easily and consistently. The main weakness of dynamic LCA is the inconsistency with traditionally static LCA. This dynamic method only covers global warming, while other environmental impacts typically covered in LCA remain static. Combining a dynamic consideration of global warming with otherwise static methods may create inherent inconsistencies, making consistent implementation in wider LCA studies difficult. It also complicates meaningful comparisons, at least if the assessments do not provide adequate reference cases for comparisons in the Preferability Framework (Huber & Fröhling 2024). Additionally, many impact categories offer different time horizons, which can be integrated within a midpoint-to-endpoint model or with a respective normalization and weighting method to match the assumed time horizon from the dynamic method.

We see that there are already methods at hand that are able to depict the GCC properly. Nevertheless, some problems do not originate directly from the methods but generally from the system boundaries and other general assumptions demanded for an LCA. In particular, defining a distinct time horizon leads to the truncation of impacts that will happen in real life but are not assessed in LCA because their effect is not within the defined timeframe. Hence, the accurate modeling of the GCC is not only hampered by biogenic carbon assessment methods but also by the LCA approach itself. Therefore, assessing the GCC or the global carbon cycle with LCA always demands caution and transparency to facilitate evidence-based decision-making and progress in understanding the sustainability of the bioeconomy.

The results of this study offer scientists and practitioners an easy and flexible decision base for handling biogenic carbon in LCA. By introducing the green carbon cycle, we want to foster the comprehension of real-life conditions. In the first place, this enhances the understanding that biogenic carbon assessment is crucial in the sustainability assessment of

Table 2 Evaluation of the features of the three main methods and their ability to handle key questions and challenges. Each key question/challenge is evaluated qualitatively

Question/challenge	− 1/+ 1 Method	GWP_{bio}	Dynamic LCA
Type of biomass: short rotation	Results do not differ significantly from advanced methods for low rotation times	More difficult to implement for little gain; published factors potentially inaccurate below 1.5 years	More difficult to implement for little gain
Type of biomass: long rotation	Only traces biogenic emissions without considering timing effects	Published GWP_{bio} factors for a range of rotation periods but not available for rotation periods above 100 years	Fully usable for all rotation periods; potential gain in accuracy of results is greater for longer rotation periods
Type of biomass: primary biomass	Only traces biogenic emissions without considering timing effects	Published GWP_{bio} factors and methodology intended for primary biomass	Published method and case studies for primary biomass
Type of biomass: secondary biomass	Only traces biogenic emissions without considering timing effects	No published factors for secondary biomass, while new calculation is difficult	Comparatively easy to adapt to secondary biomass by considering the avoided decay in place of the growth function for the dynamic LCI
The overall flexibility of the method	The tracing of biogenic emission is the same for all types of biomass but is less suited for slow-growing biomass	Low flexibility is because the calculation of new GWP_{bio} factors is highly complex	High flexibility without a significant increase in complexity for new cases
Data requirement	Low data requirement; only biogenic carbon content needs to be known	Medium data requirement: The rotation period and storage times for biomass and products must be known	Higher data requirements as the dynamic LCI requires annual data for sequestration and emissions
Consistency with the overall LCA methodology	Fully consistent with overall LCA methodology	Largely consistent with the overall LCA methodology	The dynamic approach is largely inconsistent with the overall static LCA methodology

bioeconomy. Further, understanding the implications of the selected assessment methods is also essential. To showcase the possible impacts of different assessment methods, we provided four examples revealing the approaches' strengths and weaknesses, helping practitioners understand the key factors easily. With our condensed decision support matrix, we further simplify the selection of the most suitable assessment method in scientific analysis and practical application. We want to contribute to enhanced assessments of bioeconomy activities and facilitate improved decision-making to support sustainable practice. Combined with ongoing research, this may help to return to Carlowitz's principle of sustainable use of resources, even in more complex economic systems.

Supporting information.

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Declarations

Conflict of interests The authors declare no competing interests.

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