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Exploring the climate impact effects of increased use of bio-based materials in buildings

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HIGHLIGHTS

- Three building designs with increasing biobased material content were modelled and analysed using LCA.
- Dynamic LCA was applied to account for biogenic carbon sequestration, storage and emissions.
- Increasing biobased content reduces climate impact even if biogenic exchanges are assessed.
- Time horizon, timing of forest growth and end-of-life recycling are key assumptions.
- Time horizons lower than 100 years are not enough to capture properly climate impacts from buildings.

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ABSTRACT

Whenever Life Cycle Assessment (LCA) is used to assess the climate impact of buildings, those with high content of biobased materials result with the lowest impact. Traditional approaches to LCA fail to capture aspects such as biogenic carbon exchanges, their timing and the effects from carbon storage. This paper explores a prospective increase of biobased materials in Swedish buildings, using traditional and dynamic LCA to assess the climate impact effects of this increase. Three alternative designs are analysed; one without biobased material content, a CLT building and an alternative timber design with "increased bio". Different scenario setups explore the sensitivity to key assumptions such as the building's service life, end-of-life scenario, setting of forest sequestration before (growth) or after (regrowth) harvesting and time horizon of the dynamic LCA. Results show that increasing the biobased material content in a building reduces its climate impact when biogenic sequestration and emissions are accounted for using traditional or dynamic LCA in all the scenarios explored. The extent of these reductions is significantly sensitive to the end-of-life scenario assumed, the timing of the forest growth or regrowth and the time horizon of the integrated global warming impact in a dynamic LCA. A time horizon longer than one hundred years is necessary if biogenic flows from forest carbon sequestration and the building's life cycle are accounted for. Further climate impact reductions can be obtained by keeping the biogenic carbon dioxide stored after end-of-life or by extending the building's service life, but the time horizon and impact allocation among different life cycles must be properly addressed.

1. Introduction

Humanity faces an important challenge in climate change which requires immediate mitigation measures according to the latest reports published by the IPCC [1]. As a response to this, several industrial stakeholders, including the building sector, are increasingly looking at the forest as a source of raw materials which can contribute to mitigate their climate impacts by substituting traditional non-biobased materials with biobased alternatives [2].

Life Cycle Assessment (LCA) is a tool which is widely used to compare the environmental performance of different material alternatives. Recently published reviews of LCA in the building sector have concluded that biobased building solutions offer lower environmental impacts in most of the cases if compared to non-biobased building solutions [3,4]. With the increasing

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Abbreviations: IPCC, intergovernmental panel for climate change; LCA, Life Cycle Assessment; EPS, expanded polystyrene; CLT, cross-laminated timber; GWP, global warming potential; EoL, end of life; EPD, environmental product declaration.

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development of low-energy buildings and energy supply systems with low climate impacts, further reductions can mainly be achieved by optimizing other life cycle stages [5]. This is why for low-energy buildings, processes related to the materials are starting to emerge as the most important contributors to the life cycle impacts of buildings, making the choice of materials more relevant for the life cycle impact of the building [6].

Climate impact assessment of biobased products is a complex subject. The biogenic carbon dioxide sequestration and emissions occur at different times and in different life cycle stages, and some argue that the timing of these exchanges and the alterations to the forest carbon stocks should be taken into account in LCA [7]. Moreover, others dispute that the choice of time horizon for global warming potential (GWP) should be consistent with the studied life time valid in the study [8]. It has also been argued that biobased products with a long service life, such as those used for buildings, store carbon temporarily in the technosphere, reducing the carbon dioxide concentrations in the atmosphere and avoiding radiative forcing [9]. The carbon neutrality of biobased products is often assumed due to the equivalence between the carbon sequestration at the forest level and the biogenic emissions at the end of life, as they are synchronized with the natural carbon cycle [10] [11]. However, carbon neutrality is not the same as climate neutrality and a concept referred as CO_2bio is based on this approach [12]. It is still not common that LCA practitioners account for these dynamic aspects related to climate impact when performing LCA of biobased products [13].

Dynamic LCA is a methodology proposed by Levasseur et al. [8], which makes it possible to account for most of the aspects mentioned above. The method has been used to address the biogenic carbon storage effects in long-lived products such as chairs [15], and more recently in low-energy buildings [14]. This study addresses biogenic carbon using dynamic LCA when comparing timber houses with two non biobased alternatives, including the implications from landfilling at the end-of-life. However, the method has not been used to examine a time horizon that covers both the forest growth, harvesting and then the building life cycle in an order that resembles reality.

The goal of the work presented in this article is to study the climate impact implications of increasing the biobased material contents in low-energy multi-family buildings using Dynamic LCA. An apartment block in Sweden has been used as case study, where three different low-energy design alternatives were analysed with increasing content of biobased materials. The work includes different approaches to account for the biogenic carbon storage in products and for the carbon dioxide sequestration at the forest, as well as alternative service life and end-of-life scenarios. For this, carbon sequestration data for boreal forests is used as part of the inventory data for the manufacturing of the biobased products in the building.

2. Materials and methods

This section presents the method, beginning with a description of the assessed building and the alternative designs analysed with increased biobased materials content, including an outline of the system boundaries of the LCA. Section 2.1 describes the climate impact assessment aspects analysed, and the following subsections after that illustrate the methodology exercised to analyse these aspects.

2.1. About the case study

The case study used in this article is a hypothetical building block located in Stockholm, Sweden. Two designs have been modelled with equivalent functionality in terms of the functional unit (square meters of living area for fifty years); one with a concrete structure and another with cross-laminated timber (CLT) structure, hereby referred to as "CLT design". A third design has been included, referred to onwards as "Increased bio", featuring a higher content of biobased materials than the CLT design. It follows the building system proposed by "Urban Timber", a project recently carried out by students and researchers in collaboration with industrial partners [16]. For the "Increased bio" design, mineral-based insulation and cladding have been replaced with biobased products, and a sprinkler system is included in order to comply with fire protection regulations. In short, the three designs analysed in this study represent increasing levels of biobased material content; the concrete design with zero content of biobased materials, the CLT design with around 50% biobased material content, and the "increased bio" with a prospective maximized biobased material content of 69%.

The main features of the three analysed designs are summarized in Table 1, including exclusions. The excluded materials are similar for all the designs, and therefore they do not contribute to differentiate their biobased materials content. The three designs comply with Swedish passive house standard FEBY12 [17], so equivalent operational energy uses equal to 55 kWh/m^2 have been assumed. Domestic household energy is not accounted for. The two timber-based designs are made of elements prefabricated in northern Sweden, meaning that a high amount of transport is required. The material specifications and amounts for each design used in this study are provided in Appendix A, while an outline of the data references is given in Appendix B.

The system boundaries established for this study are displayed in Fig. 1, which include some of the processes recommended by the EN15804 standard [25]. The studied system includes the forest biogenic carbon sequestration as an input for the manufacturing of biobased products, as well as the emission of this biogenic carbon at the end-of-life. Since this work is focused on aspects of climate impact assessment which are specific to biobased materials, generic assumptions have been used to account for life cycle stages such as transports and construction activities. On the other hand, life cycle stages such as product manufacturing and disposal were modelled with higher level of detailing. The operational energy was modelled using solar power for electricity supply and heat pumps for heat supply. Most of the inventory data used for the LCA calculations was obtained from Ecoinvent; with adjustments to the datasets for material manufacturing and their

Table 1
Main features of the three structures studied.

Key design features	CLT design	Increased bio design	Concrete design
Foundation and ground slab	Concrete and EPS		
Structural elements	Cross-laminated timber (CLT)	Cross-laminated timber (CLT)	Concrete
Insulation in walls and roof	Mineral wool	Cellulose fibre insulation	Mineral wool
Roof elements	Glulam and sawn timber	Glulam and sawn timber	Concrete
Coverings and details	Plywood, sawn timber and gypsum board	Oriented stranded board, plywood and sawn timber	Gypsum board
Extras	None	Sprinkler system (PVC pipes)	None
Manufacturing of elements	In factory	In factory	On-site
Exclusions	Parts that are equal for all designs such as windows, doors, roof asphalt and paint on walls		

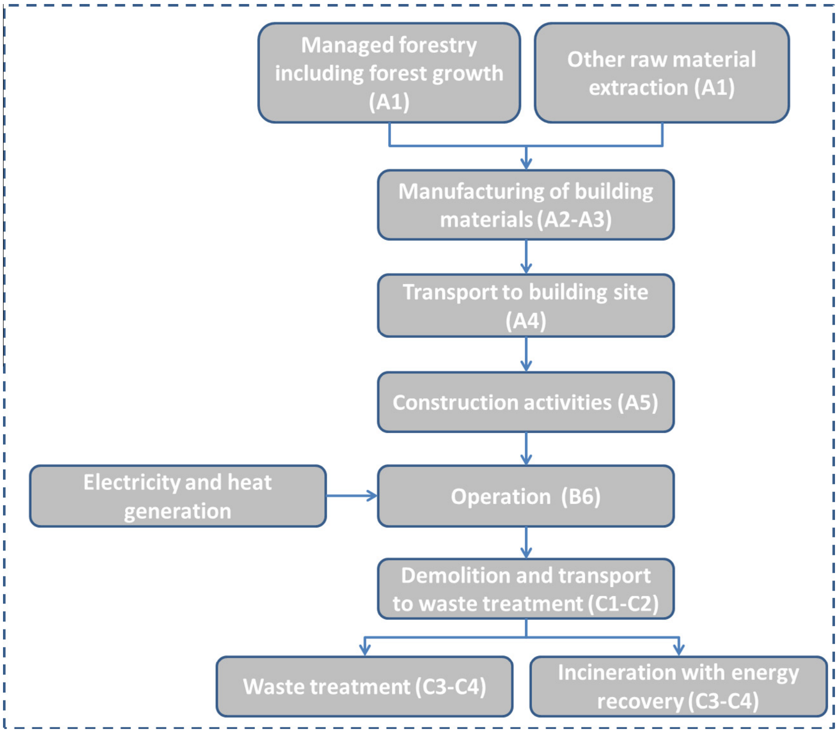

Fig. 1. System boundaries for the Life Cycle Assessment applied in the current study. The corresponding module numbers according to the standard EN 15804 [25] are given for each of the life cycle stages for better understanding.

background processes to make them more representative of the Swedish industry. The inventory data references used for the study and the adjustments and assumptions made can be found in Appendix B.

2.2. Timing of emissions and carbon storage

Dynamic LCA is a method proposed by Levasseur et al. [8] that has been used to account for the differences in timing for all the carbon exchanges in the building's life cycle. The method calculates the radiative forcing impact caused by each pulse emission on a yearly basis, allowing to establish whatever time horizon fits the goal of the study and to value each pulse emission according to when it takes place in time. The method is supported with the "Dynamic Carbon Footprinter" (DynCO$_2$) Excel tool developed by CIRAIG, which has been used to apply this method in the current study [18]. With this method the practitioner must define a time window that defines a period of time from year zero to the final year, for which the cumulated radiative forcing impact is calculated. This time window is a choice which is still subjective and does not have to be fixed to 100 years. In dynamic LCA fossil and biogenic carbon dioxide emissions and sequestration are treated equally and are assessed with the same characterization factors, as the method aims to differentiate carbon dioxide exchanges with the atmosphere according to their timing and not their source. In the case of wooden buildings, these exchanges occur in different

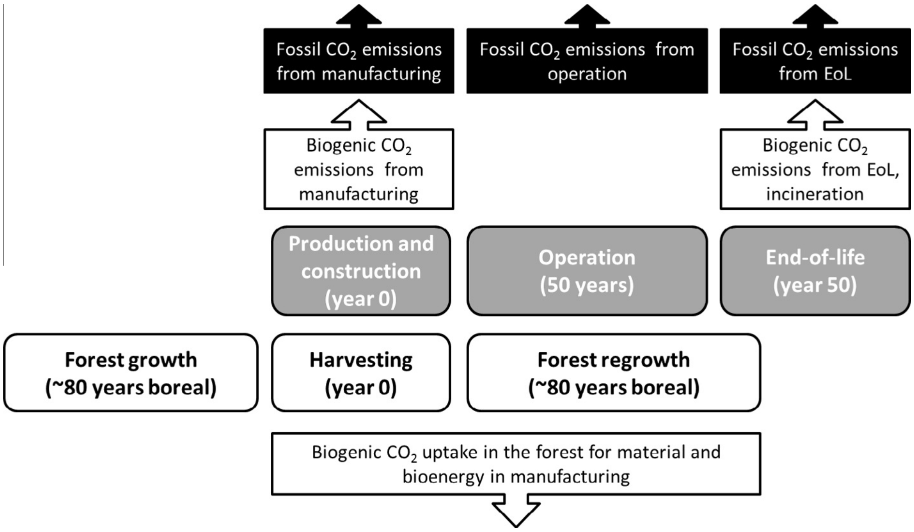

Fig. 2. The biogenic carbon dioxide exchanges between the product system and the atmosphere, as modelled in the dynamic life cycle inventory.

times during the life cycle due to carbon storage, so the effects on climate impact from this difference in timing are captured by dynamic LCA better than in traditional static assessment.

Dynamic LCA allows practitioners to have a consistency between the temporal boundaries of the study used for delimitation of the life cycle inventory and the time horizon of the characterisation factors used for the impact assessment. Dynamic LCA is flexible method enough to handle different studied time periods with yearly inventory data, so the biogenic carbon exchanges from the forest cycle can be included in the inventory.

2.3. Biogenic carbon sequestration in the forest

The Dynamic LCA method requires an inventory of GHG emissions and sequestration where the amounts of GHG released or sequestered must be differentiated by the year in which they take place. The system boundaries of this study include the forest as part of the product system for biobased materials in the building, requiring data for the carbon dioxide exchanges with the atmosphere. Fig. 2 illustrates how these exchanges have been included in the dynamic life cycle inventory. However, two possible ways to account for the biogenic carbon sequestration in the forest exist; assuming that the forest occurs before harvesting or after harvesting (as indicated in Fig. 2). It can be accounted before harvesting, hereafter referred to as “growth”, following the natural cycle of carbon in reality where the harvested biomass has to grow first. It can also be accounted for after harvesting, hereafter referred to as “regrowth”, describing a burden thinking where the harvested biomass creates a carbon debt caused by a time gap before the forest is regrown.

When modelling the carbon flows in the forest, the issue of the reference situation in the forest is raised, which has stirred some debate recently [20,24,26]. It has been suggested by Soimakallio et al. [20] to include a no-harvesting scenario as a reference situation. This should make it possible to account for foregone impact [20], allocating the difference between harvest and no-harvest forest growth to the wood products. The problem with this approach is that no biomass would be produced in a no-harvesting scenario, which would make it not applicable for the chosen functional unit. Moreover, an analysis of the difference between two product systems using LCA is known as system expansion, an approach that is only valid in consequential LCA. It is argued as well that forest growth modelling is needed to isolate the impacts from wood harvested today from past harvesting practices [19]. The reference situation used in this analysis is based on a managed forest before and after the harvesting (i.e. growth or regrowth), referred as “business as usual” by Soimakallio et al. [20].

The data for the forest carbon exchanges used in our calculations was obtained from the forest growth model in Kilpeläinen et al. [21]. The data used corresponds to the forest in northern Finland as its growth conditions are more similar to the region where the wood products in the building are produced. It is assumed that Finnish and Swedish forestry management practices are similar. The harvesting period in the simulation is 80 years, and the annual carbon sequestration in ground and above ground per hectare of forest harvested was extracted from Fig. 3 in Kilpeläinen et al. [21], for traditional timber production. On the other hand, the total forest biomass required to manufacture the materials in the building was calculated using LCI inventory data from Ecoinvent version 2.2, including energy and material input. The hectares of forest to be harvested for eighty years needed to produce this biomass were then estimated using ground productivity (m^3/ha * year) values from the Swedish official forest statistics [22]. The resulting forest area and their corresponding carbon sequestration were included as part of the system boundaries of this study. The carbon flows at the forest resulting from the calculations described in this section are presented in Appendix C.

2.4. Scenario setups studied

Four assumptions have been identified as the most relevant in dynamic LCA studies of long-lived forest products: the studied time horizon, the timing of the forest growth or regrowth before respectively after harvesting, the service life of the building and the end-of-life scenario for the biobased materials. These assumptions influence directly the timing and the amount of biogenic carbon dioxide flows to and from the atmosphere. Table 2 shows the scenario setups utilised in this study.

The baseline scenario setup for the calculations (a) consists on assuming the forest growth occurs after product manufacturing, assuming a fifty-year building service life, and assuming 90% of the biobased materials are incinerated at end-of-life. One hundred years is the most commonly used time horizon for climate impact assessment, as with the widely-used GWP100 characterisation factors from the IPCC. Considering that processes such as forest growth and building operation take place over a large time span,

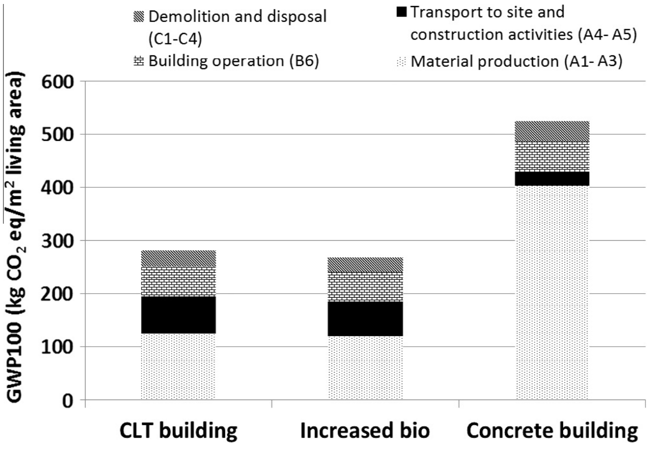

Fig. 3. Results for the life cycle climate impact assessment of the three building designs following a traditional methodological setup (static LCA model, GWP100 and assuming carbon neutrality of forest products).

Table 2
Scenario setups studied in relation with the key assumptions identified.

Scenario setups	Baseline (a)	Setup (b)	Setup (c)	Setup (d)
Service life of the building	50 years	70 years	50 years	50 years
Studied time period	Year 0–300	Year 0–300	Year 0–300	Year −80 to 220
End-of-life scenario for the biobased materials	90% of materials are incinerated Remaining 10% are recycled	90% of materials are incinerated Remaining 10% are recycled	70% of materials are landfilled Remaining 30% are incinerated	90% of materials are incinerated Remaining 10% are recycled
Timing of the forest growth	Regrowth	Regrowth	Regrowth	Growth

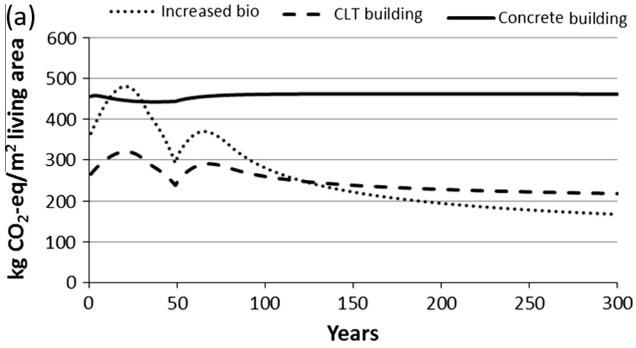

Fig. 4. Dynamic LCA results for the three building designs studied using the scenario setup (a) as described in Table 3. The figure shows the impact relative to a 1 kg CO_2 pulse emission at time zero GWI(rel) per square meter of living area. Setup (a) is the baseline setup with forest growth after material manufacturing, 50 years' service life and 90% incineration at EoL.

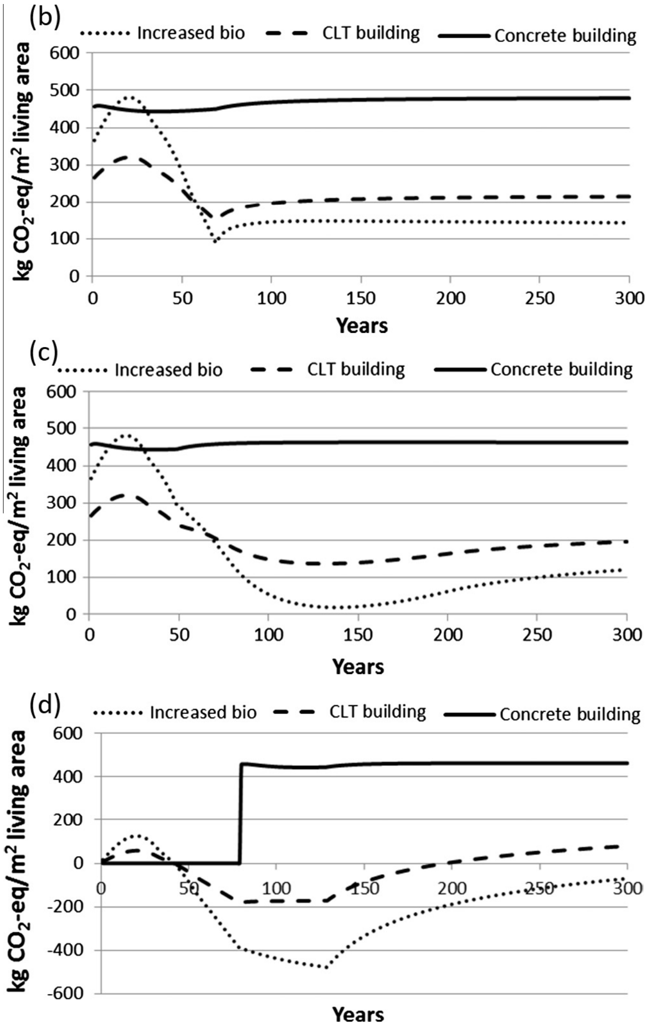

Fig. 5. Dynamic LCA results for the three building designs studied using the alternative scenario setups as described in Table 3. The figures show the impact relative to a 1 kg CO_2 pulse emission at time zero GWI(rel) per square meter of living area. In setup (b) the building's service life is 70 years, setup (c) assumes 70% recycling at end-of-life and in setup (d) the carbon sequestration in the forest takes place before material manufacturing.

a one hundred year time horizon in the dynamic LCA is not enough to capture all relevant climate impacts of a biobased building. In fact, the most common time cut-off for emissions is one hundred years after they start. As a result, in traditional LCA the emission of GHG from end-of-life landfill disposal could be accounted until up to year 150, if year zero is assumed to be when the service life begins and a fifty-year service life is assumed. To handle this problem that appears in a dynamic LCA, the emissions has been studied between year zero and year 300 for setups a), b) and c), and between years −80 to 220 for setup d). However, the year zero is not the same in setups a) to c) compared to that of setup d).

A seventy-year service life for the building has been assumed in scenario setup (b). Since no refurbishment has been accounted for, the choice of service life becomes more important, especially for traditional climate impact practice. A longer service life means that the biogenic carbon emissions at the end-of-life would occur closer to the limit of the time horizon, meaning that the effects of these emissions in the atmosphere are only observable in the results if a longer time horizon is studied.

End-of-life assumptions can also influence the results in LCA of construction materials given the uncertainty about future waste scenarios and disposal processes [23]. As there is an important amount of biogenic carbon stored in the building, the possibility of releasing this biogenic carbon through incineration or keeping it stored through landfilling or recycling makes the end-of-life scenario even more relevant in a dynamic LCA model. The implications from modifying the end-of-life scenario have been tested in scenario setup (c), where 70% of the biobased materials in the building are landfilled instead of incinerated. It is assumed then that the biogenic carbon returns to the atmosphere in the form of CO_2 by incineration of the methane from the landfill, a process that takes place during the 150 years following the end-of-life. It is worth noting that landfilling wood is not allowed in Europe, and that this scenario has been added to explore the effects of storing the CO_2 somehow beyond the end-of-life.

Finally, as Levasseur et al. [15] argue, accounting for the forest carbon balance in a dynamic LCA model raises a question regarding where in time to set the occurrence of the forest carbon sequestration, more specifically the choice between considering the forest growth before product manufacturing or regrowth after forest harvesting. The regrowth approach has been applied as the baseline scenario setup in (a), b) and c) following the recommendations by Levasseur et al. [15], meaning that the building's operation and the forest regrowth occur at the same time, as well as their impacts. Given that previous studies have found that this assumption can affect the gap between biobased buildings and other alternatives when applying dynamic LCA [14,15], the growth approach has been tested in the scenario setup (d). Scenario setup d) is in line with an inventory that is adjusted to reality, and on a stand level results in a scenario with improved temporal resolution.

3. Results

The Dynamic LCA results for the alternative setups described in Table 2 are presented in Figs. 4 and 5, while Fig. 3 displays results for a "traditional" life cycle climate impact assessment; using a static LCA model, using GWP100 characterisation factors and without considering neither the carbon sequestration in the products nor biogenic carbon dioxide emissions, thus assuming carbon and climate neutrality of biobased products. The results show that the life cycle climate impact of the three designs is sensitive to the four identified assumptions. Therefore, the climate benefits from substituting mineral-based materials with biobased alternatives in the design are sensitive to the methodological setup used when applying dynamic LCA to account for timing of emissions and biogenic forest carbon.

As can be seen in scenario setup (a) (Fig. 4), the impact from the CLT and increased bio designs fluctuates significantly for different

Table 3
Outline of the climate impact assessment results for each of the scenario setups analysed in the study. The "% reduction" values presented for the CLT and increased bio designs correspond to the difference in climate impact with the concrete benchmark. The letters a, b, c, d indicates the corresponding scenario setup and connection to Figs. 3 and 4.

Building design		Concrete building	CLT building		Increased bio	
			Climate impact	% reduction	Climate impact	% reduction
GWP100 (traditional LCA, baseline setup) (kg CO_2 eq/m^2 LA)		487	281	42%	268	45%
Dynamic LCA – AGWP100 (kg CO_2 eq to a 1 kg CO_2 emission at time zero per m^2 living area)	Baseline (a)	462	260	44%	281	39%
	With 70 years' service life (b)	468	197	58%	146	69%
	With 70% EoL landfilling (c)	462	149	68%	56	88%
	With forest growth (d)	462	5	99%	−188	141%
Dynamic LCA – AGWP300 (kg CO_2 eq to a 1 kg CO_2 emission at time zero per m^2 living area)	Baseline (a)	462	218	53%	167	64%
	With 70 years' service life (b)	479	215	55%	144	70%
	With 70% EoL landfilling (c)	462	196	58%	121	74%
	With forest growth (d)	463	79	83%	−70	115%

time horizons, while the concrete alternative is more stable throughout the 300 years displayed. Both figures for CLT and increased bio have two impact peaks, in both cases these correspond to the bulk of biogenic and non-biogenic emissions generated during product manufacturing and the end-of-life incineration. However, the impacts from these bulks are counterbalanced by the forest regrowth, which lasts 80 years (the forest harvesting period) and is concentrated towards the end of this period. Meanwhile, the concrete design remains constant since there are no significant emissions besides those emitted during material manufacturing. Only one small increase is caused by end-of-life emissions. Fig. 5(b) also features considerable fluctuations for the increased bio and CLT. There, the forest regrowth sequestration during the harvesting period (80 years) and the end-of-life emissions after the service life (70 years) occur around the same time. This causes that, in contrast with Fig. 4, there is only one impact peak, and the impact almost stabilizes thereafter.

The situation in Fig. 5(c) is similar to that in Fig. 4 up until year 50, when instead of the end-of-life emissions caused by incineration; the biogenic carbon stays outside the atmosphere as the materials are landfilled instead. Since the carbon sequestration due to forest regrowth still continues, the impact from this sequestration is not compensated in one year with the end-of-life incineration emissions, and instead is compensated slowly during 150 years. This causes the net impact to stabilize at a much lower rate until the whole of the biomass in the landfilled is degraded and returns to the atmosphere. The situation in Fig. 5(d) on the other hand is more complex. The fluctuations during the first 80 years correspond to the fluctuations in net carbon balance of the forest growth, while the emissions from material manufacturing in year 80 counteract these emissions to some extent. In the end the end-of-life emissions in year 130 (after the service life of the building ends) begin to neutralize the forest growth sequestration and increase the impact for the remaining of the 300-year time horizon.

An outcome in almost every studied scenario setup is that increasing the biobased material content of the building results in a reduced climate impact. Further reductions could be reached if the impacts from transport are reduced. Climate impacts from transport are particularly high for this case study due to the two wood alternatives requiring prefabrication, and the long distance between the factory and the building site. However, these are case-specific issues, which can be reduced by changes in means of transportation or supplier location. Despite the contribution from transports, the results were always favorable for the designs with a high content of biobased materials. Meanwhile, the methodology used in this study not only includes all biogenic emissions and sequestration, but also accounts for effects from carbon dioxide storage in products.

Table 3 presents a summary of the results presented in Figs. 3–5, as well as the difference in climate impact obtained with each setup with respect to the concrete design. Given that the results in Figs. 4 and 5 include a wide interval of values of 300 years, only the results at year 100 and year 300 are presented in Table 3, and compared to the results obtained with traditional LCA (Fig. 3). The difference with the concrete design is always positive, and is higher for the Increased bio design in all the scenario setups, giving an indication of the positive effect of biogenic carbon storage in biobased materials.

4. Discussion

The effects from increasing the content of biobased materials in a building have been studied by using dynamic LCA to assess the climate impact from three alternative designs with equivalent functionality and incremental content of biobased materials. In order to account for non-traditional LCA aspects such as biogenic carbon dioxide sequestration in the forest, storage in products and emissions at end-of-life; the dynamic LCA method has been applied in combination with approaches to model forest carbon sequestration as growth or regrowth. In order to test the influence of key assumptions in the results, different scenario setups were tested concerning building service life and end-of-life scenario.

The results show that the choice of the timing of the carbon sequestration in the forest has significant implications in the outcome of the study. The difference between the climate benefits from increasing the biobased material content of the building more than doubles if the timing of the forest growth changes, whichever time horizon chosen. As Levasseur et al. [15] have pointed out, this choice is particularly complex as there is no technical ground to make a decision that reality fits if the assessment is made in a stand level. Moreover, choosing the forest growth approach would mean that the dynamic GHG inventory starts 80 years earlier than with the forest regrowth approach, increasing the relevance of the choice of time horizon, as results also demonstrate.

In the growth approach explored in scenario d), the forest biomass has actually been standing for 80 years prior to the start of the service life of the building, making it more adjusted to what occurs in reality. In this case, the time required to cover all the sequestration and emissions in the studied system would total 130 years; 80 years of forest harvesting and 50 years of the building's service life. Given that the traditional practice in climate impact assessment in LCA is to use a 100 years' time horizon, it can be assumed that at least 100 years are needed to capture the impacts from a pulse emission or sequestration after it takes place. Following this logic, the total time horizon for the dynamic LCA of the building should be at least 230 years to include the impacts from all the emissions and sequestration that occur in scenario d). In contrast, following the same logic for scenario a), a time horizon of 180 years would be enough since all the emissions and sequestration take place within a period of 80 years. Whatever the case, the 100-year time horizon that is traditionally used in LCA practice for climate impacts would be too short to capture all the impacts from the studied system. The effect of the choice of time horizons for both scenarios, displayed in Table 3, demonstrate the importance of this choice, as in all scenarios significantly different results are obtained for time horizons of 100 years and 300 years. In other words, the choice of time horizon is highly important for the outcome, and in order to make this choice all the other methodological choices should be kept in mind.

Whenever there is an increment in the storage period of biogenic carbon in products, either by expanding the building's service life or by recycling the materials at the end-of-life, there also is an increase in the time gap between carbon dioxide sequestration and emissions. This gap increase means that the biogenic carbon sequestration in the forest starts earlier than the emissions at end-of-life, and so the climate impact reductions caused by the sequestration are higher than the negative impact from the emissions due to the longer time they affect the atmosphere. This favors use of biobased products where carbon dioxide is stored for long periods of time, and is how dynamic LCA captures the benefits from carbon storage. As a result, the service life and end-of-life scenario assumptions need to be considered thoroughly if dynamic LCA or any method that account for timing is to be applied to biobased products, so it fits the purpose of the study.

The results in Table 3 demonstrate that increasing the service life of a building with a high content of biobased materials results in lower climate impacts if timing of emissions and biogenic forest carbon are accounted for. In Table 3, the difference between the results obtained with the baseline setup and the setup with 70 years' service life decrease when adopting a longer 300 year time horizon. This is another indication that a one hundred year time horizon is not enough time to capture all the life cycle impacts from the building as only thirty years of climate impact from the biogenic emissions at end-of-life fit into the time boundary of the scenario setup. The choice of service life is particularly challenging for any kind of building in LCA practice in relation to the uncertainty associated with future scenarios, but the positive impact from extending the service life of building can be seen as an argument for long-life designs. Nevertheless, the results in Table 1 also demonstrate that the climate impact reductions achieved by extending the service life are not significantly high, and could even be counteracted by the impacts from increased maintenance and repairs if the service life is extended.

Delaying the return of biogenic carbon dioxide to the atmosphere can also be achieved by keeping the biobased products stored outside the atmosphere after the end-of-life instead of incinerating them. The result in Table 3 reveals that landfilling of a significant share of the biobased materials after disposal can also reduce the climate impact of the building. On the other hand, end-of-life scenarios of buildings are highly uncertain as they take place in the distant future, and optimistic assumptions regarding future scenarios should be made carefully. Another way to achieve this is by recycling or reusing the materials, even if with current technologies the possibilities to reuse or recycle biobased products are limited, and the amount of times that forest biomass can be recycled is also limited. As a result, the return of the biogenic carbon dioxide in the product to the atmosphere cannot be delayed indefinitely, but has to be somehow included in the inventory. Moreover, if the biobased products are recycled, the impacts from the biogenic carbon exchanges (sequestration and emission) related to the biomass in those products must be allocated between the building materials and the product(s) in which the biomass is recycled after end-of-life.

The overall results of the study show that the assumptions tested in this study can all influence the climate impact results for buildings with high content of biobased products, as well as the comparison between designs with different biobased materials content. Nevertheless, each of the studied assumptions influences the results in a different manner, being the choice of time horizon and the assumption of the timing of forest carbon sequestration the ones that affected the outcome of the result the most. The results also reaffirm that using biobased building materials results in reduced climate impacts, given that all the scenario setups tested resulted in a lower impact for the CLT design and even lower for the increased bio design, and different assumptions only changed the gap without affecting the ranking between alternatives. Moreover, the fact that this outcome occurred despite accounting for biogenic carbon dioxide not only suggests that the traditional assumption of climate neutrality in LCA of biobased materials is safe, but also that the benefits from increasing biobased materials in buildings could be underestimated in certain cases.

The results obtained for the setups where the service life and timing of forest carbon sequestration assumptions are tested (setups b) and d), differ significantly from all the others when one hundred years is chosen as time horizon, being the difference more dramatic for setup d). This is consistent with the results obtained by Fouquet et al. [14] and Levasseur et al. [15], where it was also found that timing of the forest growth significantly affects the outcome of this kind of study. Similarly, in the study by Fouquet et al. [15] where single-family houses were analysed, the difference between a concrete house and a timber alternative varies when a dynamic approach is applied to calculate climate impacts, even though the ranking between them stays the same, which is also consistent with the results obtained in this study. This study and the study by Fouquet et al. [14] differ not only in the type of building analysed but also in the assumptions explored besides the time horizon and timing of the forest carbon sequestration. While their study focuses on energy use and the difference between landfilling and incineration, the present study focuses on alternative assumptions regarding service life and content of biobased materials.

The uncertainty in the choice between timing the forest sequestration as growth or regrowth could be seen as a drawback of the dynamic LCA method, and therefore a limitation of the results obtained in this and other studies carried out at the stand level. Even if both alternatives are studied, no conclusive result can be given regarding which is preferable. Further research is needed to solve this issue, which could be achieved by modelling the forest carbon sequestration at the landscape level.

It is recommended that in future practice methods that account for timing of emissions are used as a complementary indicator to the traditional climate impact assessment approach (GWP100) for buildings with a high content of biobased materials. The results from this study remonstrate that such methods provide results with a perspective that differs from traditional methods, capturing the climate effects from biogenic carbon storage in products. However, if any of these methods is implemented, special attention should be given to the assumptions studied in this article. Finally, more detailed data is needed to make datasets for biobased materials more fitting for dynamic LCA applications. This data, which is not included in data sources such as EPDs, includes which GHGs are emitted, the timing of each pulse emission or sequestration, and the nature of the exchange with the atmosphere in case it is biogenic.

5. Conclusions

Buildings with higher content of biobased materials tend to have lower life cycle climate impact if biogenic carbon dioxide sequestration and emissions are accounted for, and if these are assessed according to their timing. However, the result can be substantially different if the carbon sequestration at the forest is assumed to occur before or after material manufacturing. The service life of the building can also affect the outcome of the assessment, and buildings with a shorter life span have lower associated benefits when substituting a non-biobased alternative. Different end-of-life scenario assumptions can also deliver results that differ significantly, and keeping biogenic carbon stored would increase the difference in timing between carbon dioxide sequestration and emissions.

Using dynamic LCA and forest growth data to assess climate impact from buildings with high content of biobased materials provides results with better resolution than traditional practices. The climate impacts of long-lived biobased products take place during long periods of time. Therefore, a time horizon of one hundred years is not enough to account for climate impact assessment of biobased products using dynamic LCA, and a fitting time horizon should be adopted for each specific case. The timing of the carbon sequestration at the forest in the dynamic inventory seems to be a challenge for further dynamic LCA application, considering the influence it could have on the results and the lack of a robust method to deal with this assumption.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2016.08.041.

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