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Full length article

Forest dynamics in LCA: Integrating carbon fluxes from forest management systems into the life cycle assessment of a building

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ABSTRACT

The urgent issue of climate change has sparked increasing interest in using wood to reduce buildings' greenhouse gas emissions (GHGe). While attributional life cycle assessment (LCA) methods are commonly employed to estimate GHGe from buildings, they lack a temporal distribution of carbon fluxes from biogenic materials, overlooking forest management impacts on emissions and sequestration. Consequently, we investigated the integration of forest and building systems, examining emissions associated with three different forest management scenarios at stand and landscape levels. Our findings suggest a 6 % to 81 % lower GHGe for the building using this study's approach compared to the static methodology recommended by the European Standard EN16485 in a 50 year perspective. However, the accumulated impact over the building's lifetime remains similar. Hence, both methods incentivize building designers' to use wood to lower GHGe, although the dynamic integration postpones benefits from the forests' carbon sequestration to later stages of the building's lifetime.

1. Introduction

A common method to assess the climate impact of buildings is attributional life cycle assessment (LCA), which aims to describe greenhouse gas emission (GHGe) flows within a chosen system boundary. The European Committee for Standardization (CEN) standard EN15978 (CEN, 2012b) specifies a standard methodology for LCAs of buildings, and EN15804 (CEN, 2012a) defines product category rules for environmental assessments of construction products. Additionally, EN16485 (CEN, 2014) sets the specific rules for the calculation of emissions from wood and other biobased construction materials, taking into account the carbon sequestration that is an inherent quality of the category of biobased materials. EN16485 prescribes the use of the so-called −1/+1 approach for wood from a "sustainably" managed forest, where the carbon sequestered in the wood (referred to as biogenic carbon) is credited to the product when it is used (−1). It means that the whole credit is attributed to the building at the time of its construction. The standard further prescribes releasing the same amount of carbon at the building's end-of-life (+1). Thereby, this −1/+1 methodology results in carbon neutrality of the wood over the reference study period (RSP). Fossil fuel supply chain emissions associated with the use of wood, such as sawmilling processes, are accounted for separately as part of non-biogenic emissions (elaborated in Supplementary Material, Section 2.3.1).

Despite the standardized approach of EN16485, criticism has persisted that the method neglects the timing of the biogenic carbon sequestration and emissions and that it does not consider all relevant biogenic carbon emissions from the forest system (De Rosa et al., 2017; Levasseur et al., 2013). The concerns can be summarized into three categories: (1) The emissions associated with the loss of forest carbon pools due to harvest are not adequately accounted for, including harvest-induced increases in CO_2 emissions from decomposing harvest residues, and disturbance of forest deadwood, forest floor and soils (Skytt et al., 2021). (2) The timing of the biogenic carbon sequestration and emissions in the forest after harvest is not considered relative to the buildings' RSP. The reasoning behind this criticism is that long timespans are involved before regenerating trees reach timber size and that emissions from decomposing residues are not instant, all together speaking in favor of distributing the benefits and emissions over the buildings' RSP instead of attributing the net flux to the time of construction (Guest et al., 2013; Head et al., 2019; Levasseur et al., 2010; Skytt et al., 2021). (3) The accounting does not adequately consider if

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the wood is sourced from "sustainably" or "unsustainably" managed forests. Complications of the criticism are that the impacts of harvest on carbon and biodiversity are often confused (Mather-Gratton et al., 2021).

Existing studies indicate that different biogenic carbon accounting approaches in LCAs of buildings substantially affect the magnitude of the GHGe resulting from a building's construction and maintenance (Andersen et al., 2024b; Hoxha et al., 2020). When comparing GHG impact results for alternative building design solutions as a basis for advice on GHGe reductions to policy and industry, it is critical to clarify whether the outlined criticisms are justified and whether significant revisions of the accounting methods are needed if the LCA should reflect the actual GHGe of the different solutions. To address this, we examined the following research question:

- How does the inclusion of biogenic carbon sequestration and emissions from natural forest systems in LCAs, in either a static or dynamic manner, influence the GHG impact results and design incentives for buildings?

Based on a review of theory and practice, we developed a method that integrates forest system carbon accounting methods with the existing LCA methods for estimating GHGe of building designs using wood for their construction. We used Denmark as a case. The main challenge related to the coupling of the forest and product systems is reconciliation of the forest system's area-based accounting and the building system's product-based accounting. However, this study suggests an approximated approach for doing so. While it is conducted in a Danish context, the proposed methods are generic and can be used in any LCAs that involve wooden buildings.

2. Materials and methods

To make the accounting of the forest and product systems compatible, we converted the area-based emission estimates for the forest system to a product-based emission estimate. In agreement with the method for allocation in LCA, we included carbon sequestration and emissions associated with the construction products within our LCA system boundaries, leaving out sequestration and emissions associated with the energy wood generated as a side product from timber harvest and wood processing in the industry. Thus, the carbon fluxes of the forest systems only include biogenic sequestration and emissions, whereas the product system also comprises non-biogenic emissions, counting the ones associated with forest management practices. The modeling of the forest system can be found in Supplementary Material II.

2.1. Simulations to calculate emissions from the forest system

Two forest management scenarios were defined to represent two different silvicultural systems. Both were assumed to be in similar site conditions, on fertile soil. The first was close-to-nature silviculture, in which mixed deciduous forest is managed in an uneven-aged structure with selective cuttings in a continuous cover system (CtN). The second was a plantation system, in which Douglas fir conifer forest is managed in even-aged stands with discrete thinning events and a final clear-cut at a rotation age of 100 years (CC) (Table 1). The CC scenario was implemented as two sub-scenarios with different biomass harvesting intensities, one assuming 80 % of the crown residues in thinnings and clearcut harvest were removed, and 20 % were left to decay in the stand (CC_{hi}), and one in which all the aboveground crown residues from thinnings and clear-cuts were left to decay in the forest (CC_{li}). The

Table 1
The characteristics of the close-to-nature multiple layer European beech (*Fagus silvatica*) management scenario (CtN) and the even-aged Douglas fir (*Pseudotsuga menziesii*) plantation management scenario (CC) with their assumptions and input parameters to simulate the growth development of individual stands (S) in the VIDAR software (v. 1.0). CC was implemented with removal of 0 % (CC_{li}) or 80 % of the crown harvest residues for energy (CC_{hi}), leaving 100 % (CC_{li}) and 20 % in the stand (CC_{hi}), respectively. dbh, diameter at breast height, 130 cm above the ground.

Specification type	Scenario		
	CtN	CC_{hi}	CC_{li}
Growth model	European beech	Douglas fir	Same as CC_{hi}
Site index	Beech site class 1 (Møller, 1933) at age 48, based on Fig. 2, site 1008 in Nord-Larsen & Pretzsch (2017a) and growth models integrated in Vidar (Meilby, 2009)	Douglas fir site class 1 (Karlberg, 1961) at age 48, based on Fig. 2, site 1008 in Nord-Larsen & Pretzsch (2017a) and growth models integrated in Vidar (Meilby, 2009)	Same as CC_{hi}
Silvicultural system	Continuous cover close-to-nature multiple layer management with natural regeneration in gaps. Implemented by assuming an equal amount of trees in age class 0–10, 10–20....90–100, and 100–110 years in a stand. Trees of the oldest age class are removed every 10th year, corresponding to a target diameter of 50 cm.	Even-aged plantation managed in a clearcutting system with a rotation age of 100 years. Thinning is conducted proportional to age with stem reduction to a target basal area of 25 m^2 ha^{-1}, starting at age 20, and an end basal area of 40 m^2 ha^{-1} at year 100, to reach a target diameter of 50 cm (cf. VIDAR specifications, Meilby (2009))	Same as CC_{hi}
Application of stand and landscape level	Since all stands in the landscape have the same tree age class distribution within the stand, there is no difference between the application of stand and landscape levels for carbon sequestration and emissions.	At stand level, the carbon sequestration follows the growth pattern for a single stand, and similar with emissions from decomposition. The landscape level assumes a normal forest with an equal area of each age class (0–10, 10–20….90–100 years), with replanting of a 10th of the forest area every 10th year.	Same as CC_{hi}
Allocation of harvested tree biomass to timber, primary energy biomass, and above and belowground harvest residues left in the forest as deadwood	Removal of stemwood of trees with a dbh > 50 cm as timber. For the chosen site index, 50 cm is reached at age 107 years. Crown residues, stumps and roots of cut trees are left to decay on the forest floor, and in the ground, respectively.	Removal of all aboveground biomass in thinnings for energy for dbh <20 cm. Removal of stemwood in thinnings for dbh >20 cm including final felling as timber. For crown residues, 80 % are removed for energy, leaving the remaining 20 % for decay on the forest floor. Stumps and all roots of cut trees are left to decay in the ground.	As CC_{hi}, except all harvest crown residue materials are left to decay on the forest floor.
Allocation of timber to product and secondary energy biomass	It is assumed that 50% of the stemwood removed as timber ends up in harvested wood products (HWP) while 50% ends up as waste from sawmill processing, and that these industrial residues are used for other purposes than construction, like energy (Brownell et al., 2023).		
Allocation of carbon sequestration and emissions to timber and energy wood	We applied economic allocation of the sequestered and emitted carbon according to EN15804. It is assumed that timber prices are 500 DKK m^{-3} and energy wood prices 200 DKK m^{-3} (Galsgård and Dansk Skovforening, 2019). This results in an allocation of $(500/(500 + 200))\cdot 100 = 71$ % for the HWP, and 29 % for the energy wood. The sensitivity of the results to the applied allocation principle is investigated in Supplementary Material, Section 4.		

emissions from these forest systems were calculated by the use of an accounting methodology similar to the one applied by Taeroe et al. (2017) for an area-based LCA comparison of emissions associated with different forest management scenarios and by Nielsen et al. (2022) for the national reporting to United Nations Framework Convention on Climate Change (UNFCCC).

All forest systems were modeled at a stand- and landscape level respective, where the emission profiles of the stand-level scenarios depict time-distributed emissions based on the growth and harvest of the subsequent stand, the landscape-level scenarios reflect a landscape with different age classes, characterized by an even distribution of the area to all age-classes. In such a landscape, the forest undergoes continuous regeneration as mature trees are harvested, which means that the average annual emissions do not show a trend, supported by several authors engaged with forest accounting of products (Berndes et al., 2016; Cowie et al., 2018, 2021).

$$CO_2\,forest(y)\ \left(kg\ CO_2eq\ m^{-3}\right) = \frac{forest\ fluxes(y)\ (kg\ CO_2\ eq\ ha^{-1}) -\ CO_2\ HWP(y)\ (kg\ CO_2\ eq\ ha^{-1})}{Harvested\ wood\ (m^3\ dry\ matter\ ha^{-1})} \tag{1b}$$

The stem volume growth of the individual stands was modeled using the software VIDAR, which include growth models for several species and various site indexes derived from experimental data from long-term forest field trials in Denmark (Meilby, 2009). Growth models of European beech (*Fagus sylvatica*) and Douglas fir (*Pseudotsuga menziesii*) were used to represent the tree growth in the CtN and CC scenarios, respectively. The growth models in VIDAR are based on data from even-aged monocultures using discrete thinnings and clearcut harvest. Hence, it was necessary to manually simulate the uneven-aged stand structure of CtN by combining simulations of a series of even-aged monocultures. This was done by assuming an equal area of eleven age classes and harvesting every 10th year of the area with 100–110-year-old trees (Table 1). It was also assumed that natural regrowth starts immediately after harvest on the same share of the area. Wood dry mass was calculated using individual tree biomass equations for Denmark with specific equations for stem, crown, root system, total aboveground living biomass, and total living biomass, providing the shares between below- and aboveground biomass (Nord-Larsen et al., 2017). VIDAR was used to simulate the development of the mean-square-diameters and the heights corresponding to the mean-square-diameter tree as inputs (Supplementary Material, Section 3.1). The stand-level dry mass was then estimated for each biomass component by multiplying the dry mass of the mean-square diameter tree with the VIDAR simulated stem number. The annual carbon sequestration was finally calculated by subtracting the stand-level dry mass stock of one year from the stock of the subsequent year and assuming a carbon concentration of 50 % by dry mass (Huntington, 1995).

To separate the carbon sequestration associated with the harvested wood product and energy wood, respectively, the carbon of stem and crown biomass was distributed to the different end-uses, harvested wood products, energy wood, and residues left to decay in the forest (Supplementary Material, Section 3.2). The emissions from decay in the forest were simulated using an exponential decay function (Gustavsson et al., 2014) (Supplementary Material, Section 3.3). The clearcut harvest was additionally assumed to result in a minor loss of 3 Mg SOC ha^{-1} over 30 years, i.e., 0.1 Mg SOC yr^{-1} from age 1 to 30, with recovery in the next 30–60 years. The assumptions were based on a global review finding that clear-cut harvest generally results in forest floor and soil C reductions of <10 % (Mayer et al., 2020), with no clear indications that such losses occur in Denmark (Nielsen et al., 2022). The forest carbon fluxes were converted to CO_2 equivalents by multiplying with the molecular weight of CO_2 relative to carbon (~44/12), as this is the unit used to calculate GHGe from buildings, cf. Section 2.2.

The transformation of the area-based total *forest flux* emissions to a product-based emission estimate was done by summing up the CO_2 corresponding to the C sequestered in the harvested timber (CO_2 HWP) (Eq. (1a)) and in the harvest residues, considering also the release of CO_2 from soil and residues left to decay in the forest (CO_2 forest) (Eq. (1b)) and distributing these to the harvested timber by dry mass:

$$CO_2\,HWP(y)\ \left(kg\,CO_2eq\,m^{-3}\right) = \frac{CO_2\ in\,harvested\,wood(y)\ (kg\,CO_2\ eq\,ha^{-1})}{Harvested\,wood\ (m^3\ dry\,matter\,ha^{-1})} \tag{1a}$$

2.2. Simulations to calculate emissions from the product system

To ensure alignment with prevalent building practices, we selected a real-life building case, one of 45 buildings presented in (Andersen et al., 2023, 2024b, 2024a) (Supplementary Material, Section 3.4, for details). We applied LCA following EN15978 (CEN, 2012b) to assess the GHG performance of the case building. The LCA was limited to include the life cycle modules A1-A3, B4, C3, and C4, aligning with the approach of assessing embodied emissions in the Danish Building Regulation (Danish Authority of Social Services and Housing, 2023). These modules cover emissions associated with raw material supply (A1), transport of raw materials to the manufacturer (A2), manufacturing (A3), replacement of materials (B4), waste processing (C3) and disposal of materials at the end of the RSP (C4). Although operational emissions related to energy consumption during use are typically included in LCAs of buildings, they were omitted from this assessment for simplicity and as they would not influence the results.

The GHGe was modeled using the Danish software LCAbyg (BUILD, 2023). LCAbyg uses generic environmental data from the database gen_dk, which are integrated into LCAbyg, based on the German database Ökobau (BUILD, 2023; *Ökobaudat*, 2019). However, as Ökobau is a generic database that is not necessarily geographically and technologically representative of Danish conditions, we used Environmental Product Declarations (EPD) data for the structural materials in the buildings, i.e., wood and concrete (Stapel et al., 2022; Tozan et al., 2022). The biogenic carbon was omitted from the assessment to allow the use of our own detailed calculations of the sequestration and emissions from the forest system. To test the sensitivity of the results to the length of the RSP, we used the Danish standard 50-year RSP (Danish Authority of Social Services and Housing, 2023) and a 100-year RSP, which also corresponds to the rotation age of the Douglas fir forest scenarios. To harmonize units to kg CO_2 eq m^{-2} and kg CO_2 eq m^{-2} yr^{-1}, we divided the embodied emissions by the gross floor area of the building and the RSP.

2.3. Integration of the accounting of emissions from the forest and product systems

The methodology developed for linking the forest and product systems was inspired by the approach suggested by Head et al. (2020). Knowing the quantity of wood in the case building, we multiplied it with the CO_2 sequestered per m^3 of HWP and the emissions from soil and decomposing residues from forest systems per m^3 of HWP (Eqs. (2a) and (2b)):

$$CO_{2,wood}\,HWP(y)\ (kg\ CO_2eq) = CO_2\ HWP(y)\ \left(kg\ CO_2\ eq\ m^{-3}\right)\cdot quantity_{wood}\ \left(m^3\right) \tag{2a}$$

$$CO_{2,wood}\,forest(y)\ (kg\ CO_2eq) = CO_2\ forest(y)\ \left(kg\ CO_2\ eq\ m^{-3}\right)\cdot quantity_{wood}\ \left(m^3\right) \tag{2b}$$

The forest system was coupled with the product system in both a static and dynamic manner. In the static approach, the average forest CO_2 fluxes of the forest system ($CO_{2,wood}$ forest) and the embedded CO_2 in wood products ($CO_{2,wood}$ HWP) of the same year were added as single pulse emissions in year 0 (A1–A3), together with all product stage emissions belonging to the product system. By the end of RSP, the CO_2 embedded in the wood products was emitted as if incinerated (Table 2), even if it could also mean disposal in a landfill, reuse, or recycling. Hence, conceptually, the carbon was transferred to another system, as required by the methodology of the European Standard EN16485 to prevent double accounting (CEN, 2014).

In the dynamic LCA, the forest CO_2 fluxes ($CO_{2,wood}$ forest) were added gradually starting at year 0 with continuous forest fluxes over the entire RSP. At the stand level, the net sequestration or emissions were distributed over the RSP according to the 'regrowth after harvest'-principle. It means that trees are replanted (CC), or the natural stand regeneration starts (CtN), at the year 0 of construction and sequesters carbon over the RSP following the growth pattern of the stand. Thereby only the part of the forest sequestration that occurs within the RSP is credited in the LCA. As in the static LCA, the biogenic carbon emissions embedded in the wood by the end of the RSP were emitted (C3) (Table 2).

3. Results and discussion

3.1. GHGe profiles of the forest system

For all forest management scenarios, we found that the carbon sequestration per hectare in the living tree biomass constituted the major share of forest-related GHGe, whereas GHGe from soil and harvest residue, stump and root decay were smaller (Fig. 1). Comparing the three forest management scenarios at stand level (Figs. 1a, c and e), the temporal distribution of GHGe differed between CtN(S) and CC(S) scenarios. Carbon sequestration and emissions in CtN(S) only had minor fluctuations due to the continuous cover management system's partial harvest every 10th year. In contrast, forest carbon sequestration in CC(S) scenarios followed the typical growth development of an even-aged stand, with the sequestration peaking around year 20, after which it slowly declined. The emissions from residue, stump and root decay were largest just after clearcut harvest, with a pulse at each harvest event. The net GHG sequestration and emissions of CtN(L), CC_{hi} (L) and CC_{li}(L) all showed similar trends at the landscape level due to the normal forest management assumption (Figs. 1b, d and f). The harvested wood in each scenario amounted to 747 (CtN) and 485 (CC) m^3 dry mass ha^{-1} over 100 years. Over the entire forest simulation period, CtN(S) had the highest accumulated GHGe per harvested wood (−877 kg CO_2 eq m^{-3} HWP), followed by CC_{li}(S) (−1933 kg CO_2 eq m^{-3} HWP) and CC_{hi}(S) (−2113 kg CO_2 eq m^{-3} HWP). The difference between CC_{hi}(S) and CC_{li}(S) origins from the emissions from decay of harvest residues, which were approximately 553 kg CO_2 eq m^{-3} HWP for CC_{hi}(S), and 733 kg CO_2 eq m^{-3} HWP for CC_{li}(S).

Although different kind of species and site productivity highly influence biomass production and carbon sequestration of forests (Nord-Larsen and Pretzsch, 2017), the choice of stand-level versus landscape-level as well as the system boundaries significantly affects the forest carbon fluxes of the different systems, when linking it to the product system. The emissions of the CtN scenario at the stand level were identical to the emissions of CtN at a landscape level (compared Fig. 1a and b), as all the individual continuous cover stands in the landscape are rooted in the same principle as the normal forest with even age-class distributions. This was not the case for the CC_{hi} and CC_{li} scenarios, leading to substantial differences in the emission profiles between stand and landscape level (Figs. 1d versus 1f, and Figs. 2d versus 2f). For the landscape level, all scenarios sequestered consistently around −11 to −13 kg CO_2 eq m^{-3} of HWP in the forest biomass and emitted around 2 to 3 kg CO_2 eq m^{-3} of HWP from residue decay. For CC_{hi}(L) and CC_{li}(L), the carbon exchanged to and from soil were estimated to be +/- 0.01 kg CO_2 eq m^{-3} of HWP and thus insignificant compared to the sequestration of atmospheric CO_2 in living forest biomass.

3.2. GHGe profiles of the product system

The case building had a total GHGe of 4.4 and 3.9 kg CO_2 eq m^{-2} yr^{-1} over a 50- and 100-year RSP, respectively. In the 50-year RSP scenario, the product stage (A1A3) was the main contributor to the GHGe, with an impact of 2.6 kg CO_2 eq m^{-2} yr^{-1} (Fig. 3a), whereas the remaining life cycle stages (B4, C3 and C4) each had an impact below 1 kg CO_2 eq m^{-2} yr^{-1}. For the 100-year RSP, the GHGe of the product stage (A1-A3) and end-of-life stage (C3 and C4) was halved (Fig. 3a) due to the division by 100 years instead of 50 years. Conversely, the GHGe from replacing building materials (B4) increased to 2.1 kg CO_2 eq m^{-2} yr^{-1} because of the need to replace relatively more materials and components over the longer RSP. As a result, module B4 was the largest contributor for RSP 100 years.

3.3. GHGe profiles for the integrated forest and products systems

Coupling the forest and product systems, the CC_{hi}(S) resulted in the largest accumulated net sequestration and, thus, apparently, the largest GHG benefit for the building, compared to CC_{li}(S) (Fig. 4). This was mainly due to the emissions from harvest residues being allocated

Table 2
Linking the emissions from the forest system to the emissions of the product system using a static and dynamic approach, respectively. Text in *italic* concerns biogenic emissions.

	Static approach	Dynamic approach
Year 0	Pulse emissions from non-biogenic products related to the construction (stage A1A3) *Biogenic pulse carbon sequestration associated with the harvested wood product and the forest system,* $CO_{2,wood}$ *HWP* +$CO_{2,wood}$ *forest*	Product stage is the same as static approach
Year 0 until the year before the last year in the RSP	Pulse emissions from replacements of non-biogenic building materials (B4)	Replacements are the same as static approach *Continuous biogenic carbon sequestration and emissions,* $CO_{2,wood}$ *HWP* +$CO_{2,wood}$ *forest, starting in year 0 and continuing on an annual basis until the last year of the RSP (regrowth after harvest)*
Last year in the RSP	Pulse emissions related to waste processing and disposal of non-biogenic building materials (C3-C4) *Pulse emissions related to the end of RSP of the biogenic carbon in the harvested wood product* ($CO_{2,wood}$ *HWP)*	Waste processing and disposal are the same as static approach *Biogenic carbon emissions are the same as static approach*

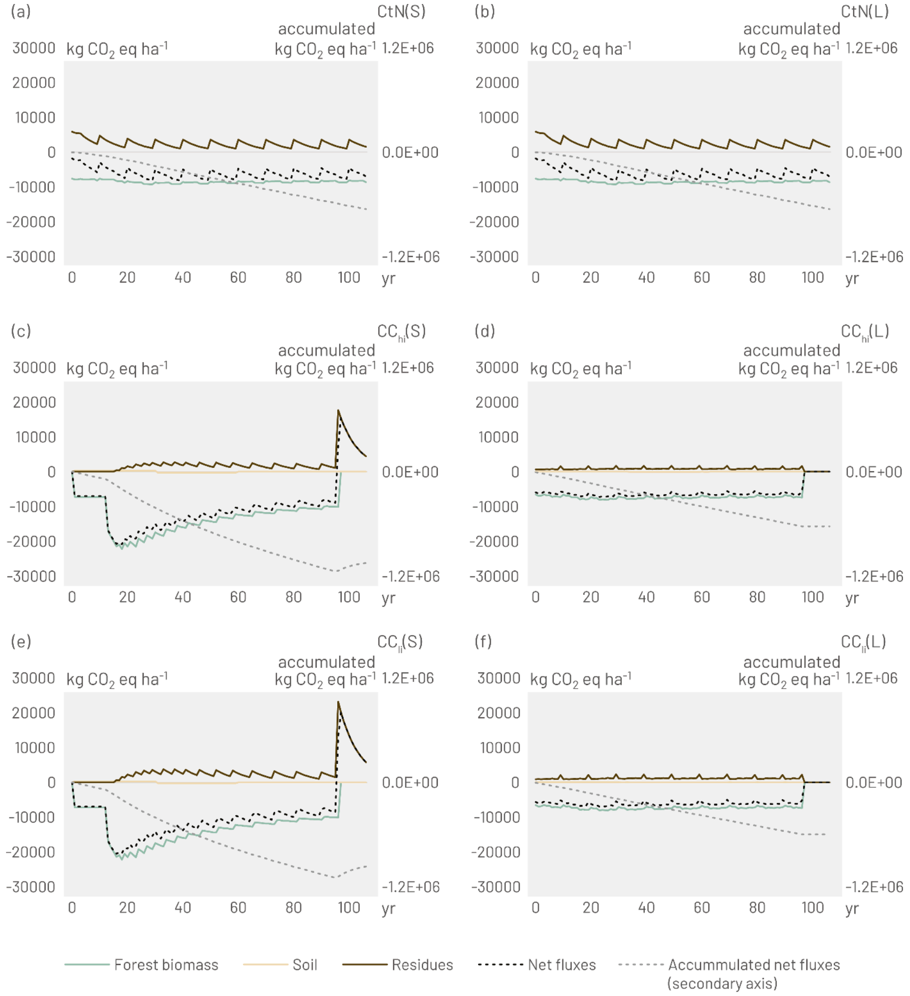

Fig. 1. GHGe profiles for forest management scenarios per hectare. Annual (primary y-axis) and accumulated (secondary y-axis) temporal GHGe profiles at a stand level (S, left) and landscape level (L, right), respectively. The included emission sources are sequestration in living tree biomass (forest biomass), and decay of forest floor and mineral soil organic matter (soil), and crown, stump, and root residues from cut trees (residues).

outside the system boundaries in CC$_{hi}$(S), but not in CC$_{li}$(S), and therefore making it a matter of modeling rather than actual GHGe of the different forest systems. The CtN(S) scenario had the largest accumulated GHGe primarily because the emissions from decay of harvest residues were included within the system boundaries, as they were for CC$_{hi}$(S). However, the lower growth rate of European Beech compared to Douglas fir in the CC scenarios also influenced the GHGe for the CtN(S) scenario.

Comparing the stand- and landscape-level approaches, considering a 50-year RSP, the CC$_{hi}$(S) scenario resulted in twice the average annual GHGe (-3.8 kg CO$_2$ eq m^{-2} yr^{-1}) compared to the corresponding landscape-level CC$_{hi}$(L) scenario (-1.8 kg CO$_2$ eq m^{-2} yr^{-1}). Similarly, for CC$_{li}$, the GHGe were -3.6 and -1.7 kg CO$_2$ eq m^{-2} yr^{-1} for the stand and landscape-level approaches, respectively, while the CtN scenario gave the same results at the stand and landscape level due to the continuous cover assumption. For the CC$_{hi}$ and CC$_{li}$ scenarios, the sequestration peaked around year 20 (before the end of the RSP), resulting in the largest share of the sequestration being accounted for in year 50. For landscape-level scenarios, the peak is distributed to a certain age-class in the normal forest landscape, resulting in the accumulated GHGe being evenly distributed over the entire RSP. Hence, the average annual and accumulated GHGe was lower in the first 50 years than the stand-level approach, where more emissions and less sequestration took place in the first 50 years of the rotation, compared to the second half of the rotation from 50 to 100 years.

For CC$_{hi}$(S) and CC$_{li}$(S), using a 100-year RSP lowers the annual average net GHGe compared to a 50-year RSP. The average net GHGe was 0.8 kg CO$_2$ eq m^{-2} yr^{-1} larger for the 50-year RSP than the 100-year RSPs. Conversely for CtN(S), the value was twice as large for the 100-year RSP compared to the 50-year RSP. However, the importance of the choice of RSP disappears at landscape level, where the difference between the 50-year or 100-year RSP is negligible for both CC$_{hi}$(L) and CC$_{li}$(L).

3.4. Comparison to standard methodology and recommendations

The approach from EN16485 results in more upfront credit than the best-performing forest management scenario, CC$_{hi}$(S). For an RSP of 50 years, the biogenic carbon sequestration from EN16485 results in -6.3 kg CO$_2$ eq m^{-2} yr^{-1} and for CC$_{hi}$(S) it equals -3.8 kg CO$_2$ eq m^{-2} yr^{-1} (Fig. 5). For a 100 year RSP, the EN16485 approach equals -3.1 kg CO$_2$ eq m^{-2} yr^{-1} and CC$_{hi}$(S) equals -1.5 kg CO$_2$ eq m^{-2} yr^{-1} (Fig. 5). The reason is that our approach takes account of the sequestration in the living biomass in the forest and the emissions from the decomposition of the left residues, stumps, and roots of the harvested trees, as well as from soil organic matter. The standard methodology only considers the biogenic carbon content in the wood products, assuming that sequestration and emissions associated with forests balance to zero over the RSP of the building.

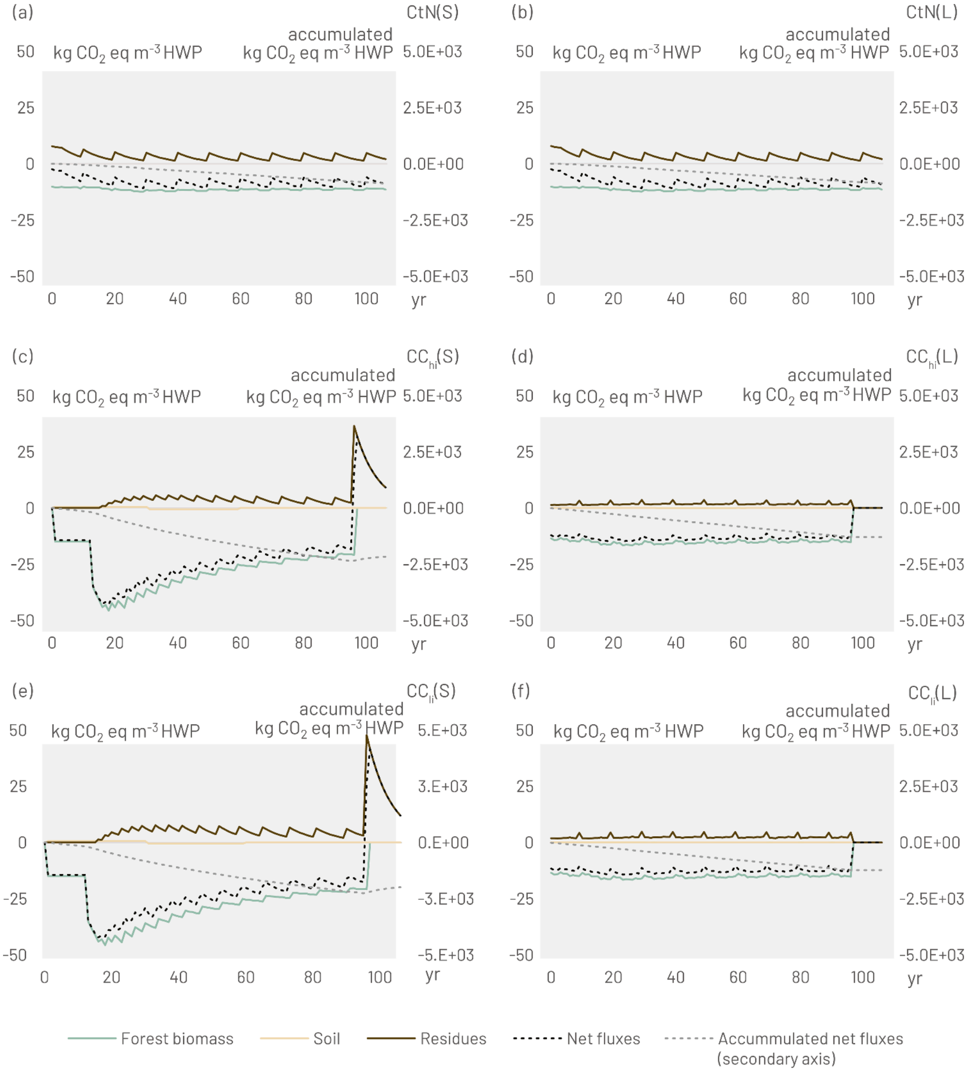

Fig. 2. GHGe profiles for forest management scenarios per m^3 of harvested wood product (HWP) produced by the forest system. Annual (primary y-axis) and accumulated (secondary y-axis) temporal GHGe profiles at a stand level (S, left) and landscape level (L, right), respectively. The included emission sources are sequestration by living tree biomass (forest biomass), and decay from forest floor and mineral soil organic matter (soil), and crown, stump, and root residues from cut trees (residues).

Considering the entire RSP of 50 years, the $-1/+1$ method of EN16485 ensures neutrality of the biogenic carbon, while this study's approach results in a net GHGe ranging from -0.2 to -2.3 kg CO$_2$ eq m^{-2} yr^{-1} for CtN(S) and CC$_{hi}$(S), respectively (Fig. 5). The carbon content of the wood products varies from -0.7 to -1.5 kg CO$_2$ eq m^{-2} yr^{-1} for CtN(S) and CC$_{hi}$(S), respectively. Altogether this gives a 6 % to 81 % lower GHGe for the building using the approach of this study compared to the method of EN16485.

The carbon content within the wood products is generally the most influential factor when estimating biogenic fluxes related to wood products used in construction. The difference in how GHGe are distributed between CO$_{2,wood}$ HWP and CO$_{2,wood}$ forest is determined by the growth level, the amount of harvestable wood in the forest, and its allocation to different end-uses. In the CtN scenarios, most of the wood produced is used for HWP, while the remaining parts of the cut trees decay in the forest. Only waste generated at the sawmill and wood industry is assumed to be used for energy and, hence, moves outside the system boundaries. Consequently, the CO$_{2,wood}$ HWP constitute most of the biogenic GHGe in this scenario. In the CC scenarios, a larger proportion of the harvested wood and biomass is used for energy or other purposes, with parts of the emissions being attributed to these end-uses, which are subsequently moved outside the system boundaries. Hence, the CO$_{2,wood}$ HWP is smaller in these scenarios.

Incorporating forest dynamics into LCAs of buildings allows reflection on temporal dynamics in GHGe of consuming wood. In particular, the stand-level approach displays the temporal changes in GHGe that are inherent for CC(S) approaches, with peaks in GHGe when the growth curve reaches its maximum, as determined mainly by site fertility and species. For CC(S) approaches, there is as such a period where the building is "indebted" until the forest carbon level is restored to the level before harvest, by growth. However, this approach has been criticized that the atmosphere rather “sees” the impacts from a landscape, rather the individual stand. In an idealized situation with a normal forest the landscape will not display a carbon debt, but be in a steady-state (Cowie et al., 2021)

Another, influential arbitrary assumption for CC(S) approaches is the choice of starting point for the forest carbon accounting. Either it can start with “regrowth before harvest”, which gives the entire carbon credit at the beginning of the building’s life cycle, or with “regrowth after harvest”, which burdens the building with a carbon debt, due to the gradual distribution of the sequestration credits and residue emission debits throughout the RSP (Hoxha et al., 2020; NCASI, 2020). There is

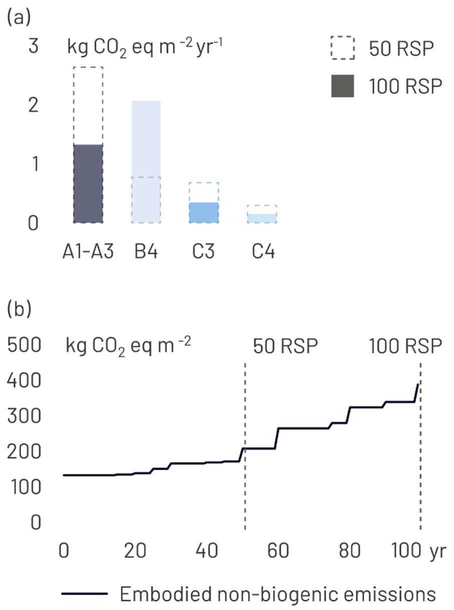

Fig. 3. Non-biogenic GHGe of building case by LCA stage for a 50-year (dashed) and 100-year (solid colour) RSP, respectively (a), and by embodied emissions over time for the 50-year and 100-year RSP, respectively (b). The embodied GHGe includes the product stage (A1-A3), replacement of building materials stage (B4), waste processing (C3) and disposal (C4).

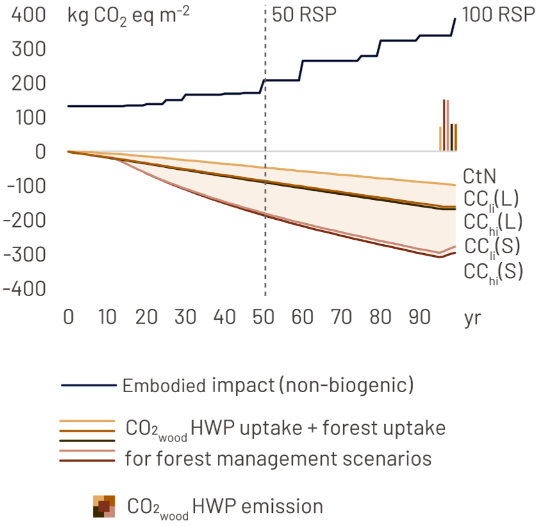

Fig. 4. Temporal cumulative GHGe profiles for the coupled forest and product systems for the 50-year (a) and 100-year (b) RSPs, respectively. The embodied emissions are all non-biogenic GHGe in the product stage (A1A3), when replacing building materials over the RSP (B4), and when considering the waste processing (C3), and disposal of building materials (C4). The net accumulative biogenic forest GHGe are shown for each forest management scenario at stand and landscape level, respectively, see also Table 1 for scenario abbreviations. The biogenic GHGe for HWP are represented with columns for each forest management scenario by year 100 of the RSP. The dashed line represent year 50 of the RSP.

no way to determine, which of the approaches that are more correct, without a subjective "political" statement about preferences for a particular purpose.

The stand-level approaches are fundamentally different from the landscape-level approach. While the stand-level approaches include the temporal dynamics from single stands, the change in scale to a landscape level evens out the fluctuations over time, as all stages of stand development are present. Similarly, all starting points are present, and hence, no arbitrary choice needs to be made. The European standard in principle takes a landscape approach. It argues that if the European forest carbon stock shows no or an increasing trend, forest management and harvesting may be considered sustainable in terms of carbon and climate (CEN, 2014). Therefore, biogenic carbon fluxes associated with the wood used in buildings can be considered carbon neutral over the building's RSP (Supplementary Material, Section 2.3.1). To the extent that it can be documented that the wood comes from a region with no decreases in forest carbon stocks, it can be argued that the landscape-level approach eliminates needs to document the exact origin of wood, in order to link it to the relevant local forest conditions and GHGe.

Both the stan- and landscape level approaches provide valuable insights into forest carbon dynamics in LCAs of buildings. However, recommending one approach over the other for use in standards must be carefully considered, since it will influence short- and long-term incentives to use wood in building design. Relying exclusively on the stand-level approach may result in sub-optimization based on a particular stand, with a risk of overlooking the overall GHGe of the forest management on the landscape level. On the other hand, relying solely on the landscape approach may overlook locally unsustainable practices, where the carbon stock of the forest decreases as a consequence of harvesting (NCASI, 2020). Hence, we recommend that both approaches are used, where possible, as each approach provides different insights at different spatial scale, and that the information is assessed jointly by experts to determine if the management is sustainable or not.

4. Conclusions

Across the forest management scenarios, we found that the sequestration in forest biomass accounted for the largest part of the GHGe from forest management compared to emissions from the decomposition of harvest residues and soil organic matter. In scenarios with clearcutting (CC), the building's performance will differ depending if you choose the stand- or landscape-level approach mainly due to omission of emission from energy wood, but also due to the different temporal distribution of the emissions, when they are transferred to the building; stand-level accounting gave the lowest GHGe for an RSP of 50 years, whereas the landscape-level accounting, as well as the close-to-nature scenario, resulted in the highest GHGe for an RSP of 50 years. Our study also supports the general understanding of wood as carbon neutral at landscape level. The approach by the European standard EN16485 gave a higher upfront credit than this study's approach due to the inclusion of forest carbon dynamics. The standard approach inherently results in carbon neutrality over the RSP of the building, while this study's approach resulted in a net credit by the end of the buildings life-time for both stand and landscape-level approaches, due to allocation of forest resources to different end uses. The different approaches offer different types of information on the effect of using wood in buildings, even if great care must be taken about implications of system boundaries when comparing forest management scenarios providing different end-use distributions of the harvested wood, where emissions from some end-uses are included while not from others. The standard approach has the advantage of simple implementation in LCAs of buildings. In contrast, the stand- and landscape-level dynamic approaches may provide valuable insights into the effect of forest management practices at the local and broader regional levels, respectively. Thus, the dynamic methods may add higher accuracy to the accounting, if high quality data can be provided, with results based on stand and landscape-level approaches supplementing each other.

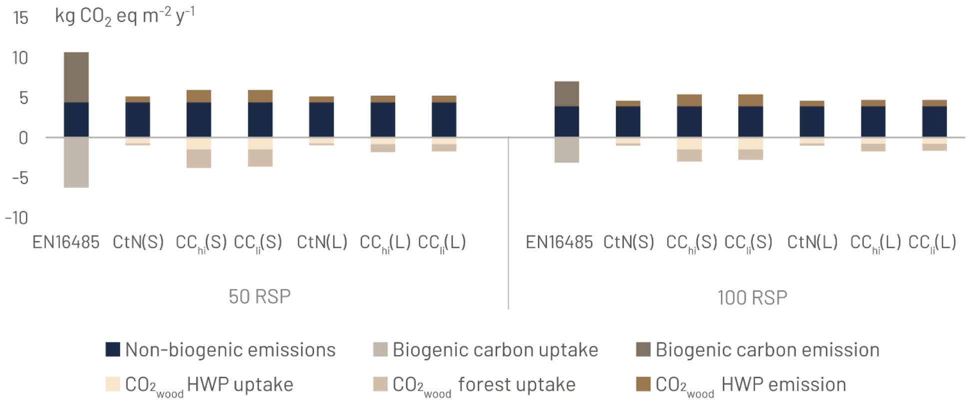

Fig. 5. Total GHGe per square meter of building per year when applying the approach of this study and the approach for biogenic carbon of the EN16485 standard (CEN, 2014), using a 50-year or 100-year RSP, respectively.

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CRediT authorship contribution statement

Camilla Ernst Andersen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Inge Stupak:** Writing – review & editing, Validation, Methodology, Conceptualization. **Endrit Hoxha:** Writing – review & editing, Conceptualization. **Karsten Raulund-Rasmussen:** Writing – review & editing. **Harpa Birgisdóttir:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

I, Camilla Ernst Andersen, state on behalf of all co-authors that the study does not relate to any sort of already published work. The study is supported financially by the Villum Foundation and Realdania, however the authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the modeling of the forest system in the attach file step.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107805.

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