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# A novel concept for dynamic evaluation of the carbon sequestration performance of sawnwood considering different forest and climate scenarios

# Ein neues Konzept zur dynamischen Betrachtung der Kohlenstoffspeicherung von Schnittholz unter Berücksichtigung unterschiedlicher Wald- und Klimaszenarien

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**Keywords:** Dynamic LCA, temporary carbon storage, climate change mitigation, greenhouse gas emissions, forest growth models

**Schlüsselbegriffe:** Dynamische LCA, temporäre Kohlenstoffspeicherung, Abschwächung des Klimawandels, Treibhausgasemissionen, Waldwachstumsmodelle

## Abstract

Trees absorb $CO_2$ from the atmosphere via their stomata and store C using photosynthesis as carbohydrates in wood. This leads to a reduction of $CO_2$ concentration – an important greenhouse gas – in the atmosphere and represents an important contribution to mitigating the climate crisis, especially if $CO_2$ remains stored in wood for a long time. This long-term storage can be fulfilled by durable wood products in the construction sector. Although this carbon storage is temporary and eventually $CO_2$ is emitted back to the atmosphere by burning or depositing wood in landfills, it still avoids direct emissions and thus facilitates medium- to long-term $CO_2$ reduction targets. However, current methods of life cycle assessment of construction products and buildings, provided by EN 15804+A2 and EN 16485, cannot quantify this effect. This

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issue has already been encountered and led to the inclusion of dynamic life cycle assessment in the 2024 annual Union work programme for European standardization.

Here we developed a comprehensible model for mapping the temporary $CO_2$ storage of durable wood products. Essential parameters for quantifying the effect of temporary carbon storage were the degradation rate of greenhouse gases in the atmosphere and the net carbon uptake in the forest during the lifetime of the construction product. The latter, amongst others, depends on the rotation times of the tree species and the effects of climate change on growth and mortality. We used a dynamic climate-sensitive forest growth model to derive the input parameters for the dynamic wood product model for a hypothetical yet typical forest stand in Austria. The adequate consideration of reuse or recycling as well as innovative approaches to end of life treatment of timber products were included in this model as input parameters.

The combination of several different modelling approaches with different outputs (forest growth model, LCA wood product model, greenhouse gas decay model and end of life model) was challenging.

The result is a modelling approach for a holistic quantification of the $CO_2$ sink of constructive timber, considering all relevant input parameters in different scenarios which vary over the time of 300 years. One key finding was identifying the minimum storage time of carbon in building products, to ensure a positive climate effect as well as the impact of different harvesting methods with related implications on carbon stock in the forest. Equally important are end of life decisions, which seem to be crucial for a positive climate mitigation effect of building products made of wood, implicating the need for intensifying research on this aspect.

## Zusammenfassung

Im Laufe seines Wachstums nimmt ein Baum $CO_2$ aus der Atmosphäre auf und speichert den Kohlenstoff nach Umwandlung mittels Photosynthese in Form von Kohlenhydrat. Dies führt zu einer Verringerung der Treibhausgaskonzentration in der Atmosphäre und stellt einen wichtigen Beitrag zur Abschwächung der Klimakrise dar, vor allem, wenn das $CO_2$ über einen sehr langen Zeitraum im Holz gespeichert bleibt. Diese Langzeitspeicherung wird vor allem durch langlebige Holzprodukte im Bausektor erfüllt. Auch wenn es sich bei diesem Verfahren um eine vorübergehende $CO_2$-Speicherung handelt, so vermeidet sie doch direkte Emissionen und ermöglicht somit mittel- bis langfristige $CO_2$-Reduktionsziele. Genau dies lässt sich jedoch mit der derzeitigen Methode der Ökobilanzierung von Bauprodukten und Gebäuden, die in den Normen EN 15804+A2 und EN 15978 vorgesehen ist, nicht abbilden. Diese Problematik wurde bereits aufgegriffen und führte dazu, dass die dynamische Ökobilanzierung in das jährliche Arbeitsprogramm der Europäischen Union für die europäische Normung 2024 aufgenommen wurde.

Ein erstes Ziel war die Entwicklung eines nachvollziehbaren Modells zur Abbildung der temporären $CO_2$-Speicherung von langlebigen Holzprodukten. Wesentliche Parameter zur Quantifizierung der Wirkung der temporären Kohlenstoffspeicherung waren die Abbaurate der Treibhausgase in der Atmosphäre und die Netto-Kohlenstoffaufnahme im Wald während der Lebensdauer des Bauprodukts. Letztere hängt unter anderem von den Umtriebszeiten der jeweiligen Baumarten und deren prognostizierten Veränderungen durch den Klimawandel ab. Hier werden diese als Eingangsparameter für das dynamische Holzproduktmodell mit Hilfe eines dynamischen Waldmodells ermittelt, das für einen hypothetischen aber typischen Waldbestand in Österreich angewendet wurde. Die adäquate Berücksichtigung der Wiederverwendung bzw. des Recyclings sowie innovativer Ansätze zur end of life Behandlung von Holzprodukten fließen ebenfalls als Eingangsparameter in dieses Modell ein. Die Kombination der verschiedenen Modellierungsansätze mit unterschiedlichen Waldwachstumsmodellen, den LCA-Holzproduktmodellen, Treibhausgasabbaumodell und end of life Modell – war nur einer der anspruchsvollen Aspekte.

Das Ergebnis ist ein Methodenvorschlag zur ganzheitlichen Quantifizierung der $CO_2$-Senke von Holz unter Berücksichtigung aller relevanten Eingangsparameter, die in verschiedenen Szenarien über 300 Jahre zeitlich variabel sind. So können unter anderem eine Mindestspeicherzeit von Kohlenstoff in Bauprodukten ermittelt werden, um einen positiven Klimaeffekt zu gewährleisten, sowie die Auswirkungen verschiedener Erntemethoden mit den damit verbundenen Folgen für den Kohlenstoffvorrat im Wald dargestellt werden. Ein weiterer wichtiger Beitrag sind end of life-Entscheidungen, die für einen positiven Klimaeffekt von Bauprodukten aus Holz von entscheidender Bedeutung zu sein scheinen, was bedeutet, dass die Forschung zu diesem Aspekt intensiviert werden muss.

## 1 Introduction

Considering the climate crisis and resulting UN Sustainable Development Goal number 13 (UN 2022) as well as the European Green Deal (EC 2019), environmental impacts of building components become increasingly important. The European Commission stressed in (COM 2020) the need to address sustainability of construction products and highlighted a more sustainable built environment as essential for Europe's transition towards climate-neutrality. In (COM 2021) the Commission identified construction as one of the priority ecosystems that face the most important challenges, meeting climate and sustainability on which the competitiveness of the construction sector depends.

Addressing these challenging issues, CEN TC 350 developed a series of standards in order to give guidance for the assessment of environmental impacts of building materials or products EN 15804 (2019), buildings EN 15978 (2012) and civil engineering works EN 17472 (2021). Moreover, since the draft of the European Construction Product Regulation (EC 2022) indicates the assessment of the environmental impact as a basic requirement (sustainable use of natural resources of construction work) with a list of essential characteristics related to life cycle assessment (LCA) to be covered, development is gaining traction.

## 1.1 Timber structures as part of the solution to climate change?

In the United Nations Framework convention on Climate Change (UN 2023), carbon dioxide removal (CDR) and storage in timber constructions is acknowledged as carbon removal and storage activities. This solution is not considered as permanent by the European Commission (EC 2009), although the duration of the $CO_2$ storage can vary considerably between products as well as between applications. Nevertheless, they can contribute to delaying emissions by prolonging the effective lifetime of carbon removals and by optimizing the end of life (EoL) phase, in synergy with the objectives of a Circular Economy. Certification challenges relate to improving the quantification methods, setting the baseline, defining the expected lifetime of durable wood products, defining responsibilities across the product value chain, and addressing the risk of carbon reversal during the use of the product and after the end of its lifetime.

Though there seems to be a European and worldwide consensus regarding positive climate effects of temporary carbon storage in timber building products, current normative and technical regulations do not reflect this approach (EN 15804, EN 15978, Zampori 2019). Therefore, the aim of this study is to conceptualize a more detailed approach by combining different systems, that are related to each other, yet currently not considered adequately in the often simplified normative and technical regulations.

## 1.2 Biogenic carbon accounting in technical standards and assessment schemes

There are several technical standards for LCA and product environmental footprint (PEF) available, which are reviewed regarding their approach to carbon accounting of bio-based building materials.

In the latest version of EN 15804, removals of $CO_2$ from the atmosphere and conversion into biomass (with the exclusion of biomass of native forests) and transfers from previous product systems shall be characterised in the Life cycle impact assessment (LCIA) as $-1$ kg $CO_2$ eq./kg when entering the product system. Emissions of biogenic $CO_2$ from biomass and transfers of biomass into subsequent product systems shall be characterized as $+1$ kg $CO_2$ eq./kg. Since the life cycle of a product is divided into modules in EN 15804, the $CO_2$ uptake (and negative greenhouse gas GHG emissions) takes place in module A1 (growth of the tree) and the positive emission to the atmosphere (or to the next product system) in the use phase (replacement) or in the end of life (EoL) phase. The flows of biogenic carbon into and out of timber, that is combusted at EoL, will result in net zero contribution to the carbon footprint of the product (as well as if the product is reused or recycled), except for any portion of biogenic carbon converted to $CH_4$. Any accounting of positive effects of temporary biogenic carbon storage and related delayed emissions of $CO_2$ is not allowed, even the effect of permanent biogenic carbon storage shall also not be included in the calculation of global warming potential (GWP). A pointless differentiation which does not affect fossil carbon storage, but can prevent efficient carbon removal and storage from atmosphere.

A similar approach can be found in EN 14067 (2018), though, in contrary to EN 15804, EN ISO 14067 at least permits the opportunity to supplementary calculate temporal discounting or time dependent characterisation factors.

The Product Environmental Footprint (PEF) method (Zampori 2019), developed by the Joint Research Center (JRC), prohibits considering credits associated with temporary and permanent carbon storage and/or delayed emissions in the calculation of the climate change indicator. This means that all emissions and removals shall be accounted for as emitted "now" and there is no discounting of emissions over time.

Some methods do already exist considering carbon storage and delayed emissions, such as the British Standard PAS 2050 (2011) and the International Reference Life Cycle Data System (ILCD) Handbook (JRC 2011). Both methods include a linear reduction factor for delayed emissions with a maximum at 100 years, leading to zero emissions.

However, there are no widely accepted ways of accounting for the time at which each emission occurs, and the subsequent climate impacts. According to EN 15804, carbon emitted at EoL is given as much weighting as carbon emitted during construction, thus ignoring the differing duration over which global warming effects can occur and with no way of accounting for the potential climatic benefits of temporary carbon storage or delayed emissions. These benefits include a reduction in cumulative climatic energy input, buying time for adaptation, delaying or avoidance of tipping points, and even the possibility of permanent storage through future technological changes (Hawkins 2021).

### 1.3 Dynamic modelling approaches

Dynamic life cycle assessment (DLCA) is an extension or adaptation of the "traditional" life cycle assessment method, which considers the temporal aspects of environmental impacts over the entire life cycle of a product. In principle, this "dynamization" can be carried out for all impact indicators, but until now the focus of such considerations has mainly been on GHG (primarily $CO_2$). In contrast to the static methods described above, in which all impacts in the period under consideration are summarized over time and thus treated equally, the dynamic life cycle assessment explicitly incorporates the timing of inputs (material, energy) and outputs (waste, emissions) in the system under consideration along with their effects on the environment. GHG emissions are considered in a differentiated manner, based on the actual degradation rates in the atmosphere. The general principle of DLCA and its relation to GWP is described in Levasseur *et al.* (2010) and further discussed in regard to the building sector in several publications such as Breton *et al.* (2018) and Arehart *et al.* (2021). Using DLCA with a dynamic climate model implemented, relevant indicators can be calculated with any GHG emissions history (Levasseur *et al.* 2010). Several studies with dynamic approach have been carried out for the comparison of biogenic and fossil fuels (Holtsmark 2015, Cherubini *et al.* 2011, Cherubini *et al*. 2012, Guest *et al.* 2012) with the assumption of immediate release of $CO_2$. This might be a reasonable approximation for fuels, but is not applicable for long lasting timber building products. In a more complex approach, Guest et al (2013) determined the GWP as a function of the rotation period in the forest and the carbon storage time. It could be shown that the higher the storage time and the lower the rotation period, the lower the related GHG emissions.

## 2 Methodology

It should be mentioned in advance, that the methodological approach of our analysis is focused on product assessment and not on national GHG reporting. These are two (methodologically) different approaches and issues which are not connected so far and executed separately by different stakeholders. Recent intentions to standardize a simplified dynamic LCA approach for timber building products are under discussion at the moment. The aim of the article is not the discussion between these two approaches, nor a general statement to $CO_2$ reduction targets, but rather to give insight regarding the advantages and opportunities of dynamic LCA as a methodology for building product assessment.

The developed concept provides GHG emission data for a selection of timber building products, generated with dynamic LCA driven by different forest development trajectories calculated with a forest growth model. In this study we use the forest model PICUS (details in the following sections). For the different timber products, a standardized product model is considered applying ISO 14040 (2006) and ISO 14044 (2006) LCA methodology as well as EN 15804 for building products in particular. To address ongoing developments in circular economy in the building sector, the EoL phase is modelled with different scenarios including incineration with energy recovery, reuse, recycling in particle boards, bioenergy carbon capture and storage (BECCS) as well as pyrogenic carbon capture and storage (PyCCS). An overview of the given approach is provided in Figure 1.

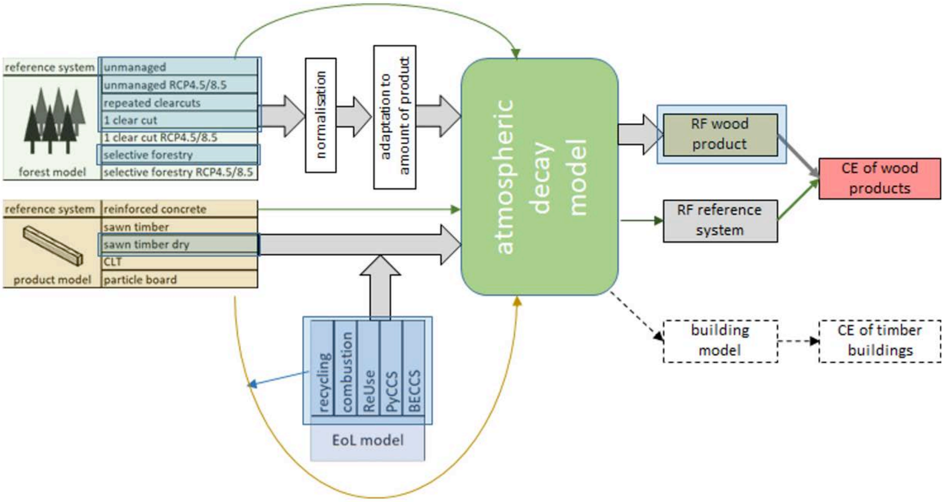

*Figure 1: Schematic overview of the chosen calculation approach of the temporary carbon storage in timber building products, showing the three different model approaches – forest/product/EoL – combined in the atmospheric depletion model. Marked in blue are components considered in this paper. RF radiative forcing, CE climate effectiveness.*

Abbildung 1: Schematische Darstellung des gewählten Rechenmodells der temporären Kohlenstoffspeicherung in Holzbauprodukten, gezeigt werden die drei Modellzugänge – Wald/Produkt/EoL – kombiniert im atmosphärischen Abbaumodell. Blau markiert sind Komponenten, die in dieser Arbeit behandelt werden. RF Strahlungsantrieb, CE Klimawirksamkeit.

Addressing the main question of the environmental and climatic benefit of the long-term carbon storage in timber building products, the functional unit of a (comparative) dynamic study is assumed to be the building or the square meter floor area of the building. For comparative reasons, the building has to be the baseline because, if timber is not used for the building, the alternatives are GHG intensive materials such as steel, concrete or bricks. This issue should not be confused with the approach of avoided emissions, also known as substitution – using wood instead of other materials – (Sathre *et al.* 2010, Pölz *et al.* 2015, Hafner *et al.* 2017), where a comparative LCA according to standardized methods show the environmentally preferable building material choice. Nevertheless, at the current stage of this research there is still no opportunity to compare dynamic life cycle impact assessments of whole buildings (WBDLCA) or building components, but can be addressed in further studies anyway.

Therefore, substitution is not considered in this study, as we focus on the product and substitution is neither a product inherent property nor part of the products life cycle.

In the following, the different models are characterized and resulting challenges as well as required assumptions of the combination of different modelling approaches are addressed.

## 2.1 Forest model simulations

### *2.1.1 Impact of greenhouse gases on global warming potential of forests*

Methane $CH_4$ and nitrous oxide $N_2O$ are important GHGs to assess the GWP of forests and forest management, in addition to $CO_2$. Many forest models, including PICUS (Irauschek *et al.* 2017, Lexer and Hönninger 2001), do not consider $CH_4$ and $N_2O$. $CH_4$ contributes about 0.97 $W/m^2$ radiative forcing (relative to 1750) to global climate change, $N_2O$ contributes 0.17 $W/m^2$. Compared to $CO_2$ with 1.68 $W/m^2$, $CH_4$ accounts for 58% and $N_2O$ for 10% of the radiative forcing of $CO_2$. $CH_4$ has an average lifetime in the atmosphere of 11.8 years and a GWP compared to $CO_2$ of 25. $N_2O$ has an average lifetime in the atmosphere of 109 years and a GWP compared to $CO_2$ of 298 (IPCC 2013). This makes $CH_4$ and $N_2O$ potentially relevant GHGs, if they are also released or influenced by forests or forest use.

Pine forests in North America (annual mean temperature 7.8 °C, 1010 mm annual rainfall, well-drained Luvisol soils) across different development stages were sinks for both $CH_4$ and $N_2O$ (Peichl *et al*. 2010). This suggests that forests can even reduce the concentration of $CH_4$ and $N_2O$ in the atmosphere. Briefly after clearcuts (up to 3 years) the uptake of $CH_4$ and $N_2O$ has been reported to be reduced, especially under cold-moist soil conditions (Gundersen *et al*. 2012, Vestin *et al*. 2020). Fertilization increases release of $N_2O$ (Siljanen *et al*. 2020), but fertilization is not common in forest management in Austria. There is evidence that species change can lead to increase emissions of $CH_4$ and $N_2O$ (Gundersen *et al*. 2012). We conclude that positive effects of forests on GWP of $CH_4$ and $N_2O$ is limited compared to GWP of $CO_2$ over the life time of a forest, if

(1) no species change occurs,
(2) no fertilization is applied and
(3) well-drained soils are present.

### *2.2.2 Forest ecosystem modelling*

We used the forest ecosystem model PICUS v1.5 (Irauschek *et al.* 2017, Lexer and Hönninger 2001) for quantifying forest growth under different management and climate scenarios. PICUS is a hybrid of gap models and mechanistic models and for a detailed description we refer to Irauschek *et al.* (2017). We considered three climate input, current baseline climate (detrended conditions of 1960 until 1990), RCP45 and RCP85. The available climate data (air temperature, vapor pressure deficit, solar radiation, rainfall) span until 2100. We used detrended data from 2000 to 2100 to extend the time period from 2100 until 2300. The average temperature for the baseline climate was 8.9 °C and annual rainfall sum 843 mm (in vegetation period 475 mm). We created a hypothetical mixed about 80 years old *Picea abies-Abies alba* forest stand to initialize the simulations with stem density of 410 trees per hectare, basal area of 32 $m^2$/ha and volume stock of 430 $m^3$/ha. Trees are generated, until the target basal area is reached, and their locations are assigned randomly. We started the simulations in year 2022. We considered the following management scenarios:

(1) no management,
(2) clearcut in 2042, thinnings in 2063, 2073 and 2083, clearcut in 2143, thinning in 2163, and
(3) continuous cover forest management with removals every 10 years.

PICUS v1.5 simulates tree growth, mortality due to competition, water stress, harvesting as well as abiotic and biotic disturbances. PICUS features a soil and deadwood module, implemented based on the TRACE model (Currie *et al.* 2004, Currie *et al* 2009). We note that the implementation of TRACE into PICUS is not yet thoroughly validated, but decided to activate it in this study, to consider soil and deadwood pools for carbon simulations, given their important contributions to overall carbon pools (Pan *et al.* 2011, Mayer *et al.* 2020). The TRACE model developed in North America has been proven to provide realistic results for ecosystems similar to those considered in this study (Currie *et al.* 2004, Currie *et al.* 1999). The considered carbon pools are live vegetation (above- and belowground), soil (including organic litter layers) and deadwood (standing and lying).

## 2.2 Product model

### *2.2.1 Methodological principles and assumptions*

As defined in ISO 14040 and ISO 14044, a product LCA is a multiphase process consisting of several interconnected steps, and outcomes are based on goals and purposes of a particular study. The methodology for Life Cycle Assessments for building products and building components is roughly provided in EN 15804 and EN 15978 respectively. With regard to GWP, EN 15804 prescribes the baseline model of 100 years of the IPCC based on (IPCC 2021). Calculation is carried out with the software SimaPro, based on ecoinvent v3.9.1 database for materials as well as for energy datasets.

Since emphasis of this study is placed on the dynamic evaluation of temporary $CO_2$ storage, assessment data from the life cycle inventory (LCI) of the different products is seen as the result of the product model and the input into the dynamic analyses.

### *2.2.2 Functional equivalents*

The product model of this study follows closely EN 15804 and EN 15978, which require identification of a functional equivalent for the building product and building component respectively, to enable a valid basis for future comparisons of other buildings. According to EN 15978, a functional equivalent is “the quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison”. In other words, the functional equivalent is a set of design criteria that buildings and building components must have in common to ensure a sound comparison. Since the whole building and the component is not defined, calculations and results refer to the standard reference for environmental assessment of timber building products (EN 15804) which is 1 $m^3$ of timber building product. In this study, 1 $m^3$ of sawnwood used for construction purposes is considered as standard reference.

### *2.2.3 System boundaries*

The system boundaries define the life cycle activities included in the analysis. The various processes occurring at each stage are classified and grouped in “modules” or “stages”, marked in alpha-numeric design A1–C4 and D (Fig. 2). This modular structure provides a consistent and transparent reporting format for environmental assessments. The system boundaries for this assessment are A1-A3 (raw material, transport and production), A4 (transport to site), C2 (transport to EoL treatment) and C3 and C4 (EoL). $CO_2$ emissions of the different life cycle stages are included into the model at the time they occur.

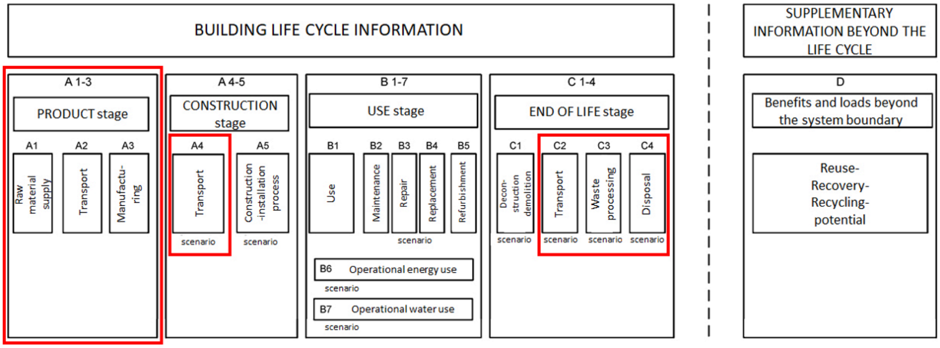

*Figure 2: Modular approach of LCA for a building product according to EN 15804, as well as for components and buildings according to EN 15978. Considered stages in this study are highlighted red.*

Abbildung 2: Modularer Ansatz für die LCA von Bauprodukten gemäß EN 15804 sowie für Bauteile und Gebäude gemäß EN 15978. In dieser Studie berücksichtigte Phasen sind rot umrahmt.

### *2.2.4 Reference service life*

The reference service life (RSL) of the material is considered to be variable, which allows us to check the impact of RSL on dynamic LCA results. Various scenarios are compared, starting with an RSL of 50 years, subsequent, recycling in plaster boards as well as reuse and recycling with an overall RSL of 300 years as a maximum. In the use phase (B) usually no emissions occur, since neither maintenance is required nor replacement of load bearing structures is necessary anyway. Nevertheless, the use phase (or even several use phases) defines the relevant time period (RSL) for the dynamic modelling.

### *2.2.5 Product data and EoL processes*

Emission data for the production of the different products has been obtained from the ecoinvent database (v3.9.1) in SimaPro (dataset for sawnwood: sawnwood production, softwood, raw, dried (moisture content 10%), representing Europe without Switzerland) and we conducted the impact assessment in accordance with EN15804 methodology (based of EF 3.1). All upstream processes required to produce the considered products are included. Economic allocation, which is already implemented in the ecoinvent datasets, was used for separating the impacts between the main product and different by-products typical in the wood production chain. Transport processes (for the construction as well as the EoL stage) have also been considered by generic data from ecoinvent v3.9.1 (dataset: transport, freight, lorry 7.5-16 metric ton, EURO6 {Europe}).

Incineration of wood as important EoL process was also considered based on ecoinvent 3.9.1 (dataset: treatment of waste wood, untreated, municipal incineration {Switzerland}), however the LCIA results were adjusted according to the actual water content of the considered products. For the recycling scenario, data relating to the production of particle board (dataset: particleboard production, uncoated, average glue mix Europe}) was used without considering the input flow of wood as this material is provided by the considered product itself at EoL. For the reuse scenario, no impacts besides transport have been considered.

Regarding BECCS and PyCCS, the considered scenarios are based on assumptions, as reliable data in this field is still quite scarce. For BEECS the $CO_2$ emissions during incineration have been reduced by 90%, this reduction factor has also been used by Hawkins *et al.* (2021). For PyCCS an LCI by Peters *et al.* (2015) has been considered as a starting point. For the actual calculations within this work only the electricity needed and the $CO_2$ emissions into air have been regarded.

### *2.2.6 Combining forest and product model*

From PICUS simulations we used the yearly carbon stock of live trees, soil (organic and mineral soil layers) and deadwood (standing and lying) and calculate the total forest carbon stock as their sum. By calculating the difference between each year's total stock value and considering losses by decomposition, a yearly carbon flux to/from the forest was obtained and subsequently converted into a yearly $CO_2$ emission or sequestration (negative emission). During this step the carbon leaving the forest system as harvested material was accounted for separately and not included in the $CO_2$ flows, as they are not relevant for the atmosphere at this time.

To link the forest-related $CO_2$ flows (with atmospheric relevance) with the analysed products, the 100-year-average of harvested wood volume from each forest system was used as a baseline in order to obtain yearly $CO_2$-flows per $m^3$ of harvested wood, specific for each forest model. These yearly flows are also representative for the functional unit of 1 $m^3$ sawnwood used for construction purposes as biogenic carbon within wood is allocated on actual physical principles, meaning each $m^3$ of harvested wood contains (on average) the same amount of biogenic carbon irrespective of its actual further processing and use. In this study only the first 100 years of forest-related $CO_2$ flows after initial wood harvest are allocated to the product. This assumption, which should be further explored and discussed in future studies, was made on the notion that 100 years after wood was originally harvested, the forest area will have most likely reached their original carbon stock and further carbon flows are not directly associated with the analysed product anymore. This assumption is also linked with the 100-year time span used for calculation of the average harvest volume. We verified this using the forest model results.

### *2.2.7 Evaluation of the impact of different greenhouse gases*

An analysis, regarding the different GHGs, has shown that only a small difference exists between the results when each GHG and its specific decay function are considered separately at first and summed up in a second step (red/orange in Fig. 3 below) and a simplified approach where all relevant emissions are considered as $CO_2$-equivalents from the beginning and modelled with the $CO_2$-specific decay function (blue in Fig. 3). This is caused by very small amounts of $CH_4$ and $N_2O$ released and their impact on the overall results is thus small. We thus decided to use a simplified approach for all subsequent calculations reducing the complexity and amount of data transfer between the different model components. $CH_4$ and $N_2O$ are included in the calculations, already converted into $CO_2$-eq. in the applied ecoinvent 3.9.1 datasets for modules A1-A3,C3 and C4.

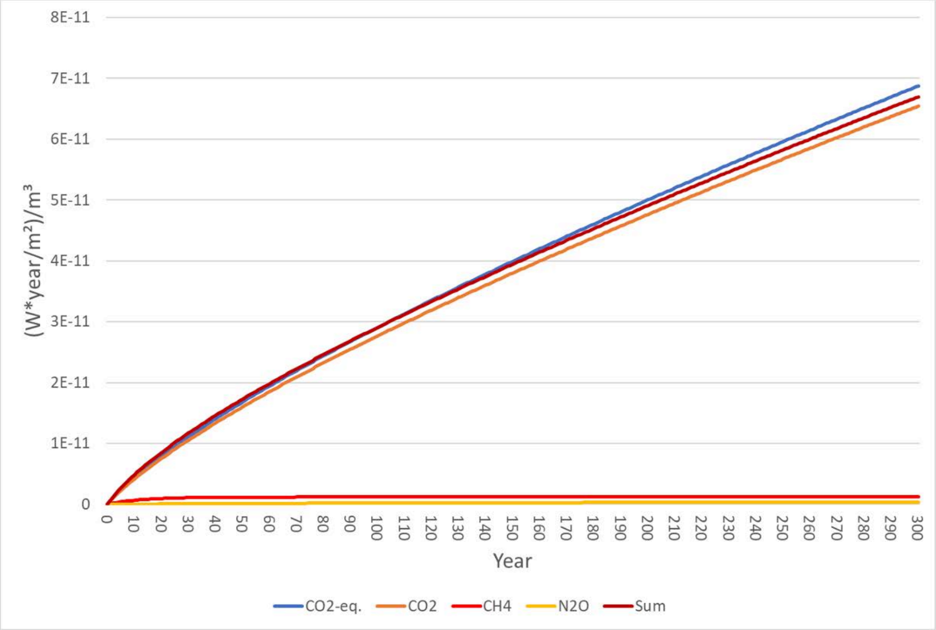

*Figure 3: Analysis of the cumulative radiative forcing based on GHG-specific characterisation compared to a simplified approach using CO2-eq. per 1 $m^3$ sawnwood.*

Abbildung 3: Analyse des Strahlungsantriebs basierend auf Treibhausgas spezifischer Charakterisierung gegenüber einem vereinfachten Zugang unter Anwendung von CO2-äqu. pro 1 $m^3$ Schnittholz.

### *2.2.8 Atmospheric decay models*

The yearly CO₂ flows for both the product itself (for all considered life cycle phases) as well as the forest-related flows associated with the product are used as input in the freely-available Temporal Climate Impacts spreadsheet tool (Cooper 2020) to obtain the CO₂ concentration in the atmosphere as well as the cumulative radiative forcing early on a yearly basis. The atmospheric decay of CO₂ is thus modelled according to Joos *et al.* (2013).

## 3 Results and Discussion

All following results include the cumulative CO₂ flux up to 300 years as well as the cumulative radiative forcing for the same time frame. When comparing two scenarios, lower negative values represent a carbon sink or less radiative forcing during the considered timeframe.

### 3.1 Forest management scenarios and climate conditions

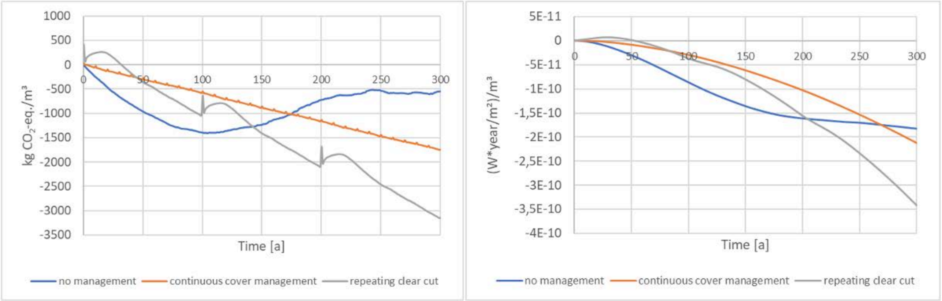

*Figure 4: Cumulative CO2 flux (left) and radiative forcing (right) of different forest management scenarios related to 1 m³ sawnwood.*

Abbildung 4: Kumulativer CO2 Fluss (links) und Strahlungsantrieb (rechts) verschiedener Waldbewirtschaftungsszenarien in Relation zu 1 m³ Schnittholz

Until about year 140 the unmanaged forest sequesters more carbon than managed alternatives and thus has also better cumulated radiative forcing (Fig. 4). The forest considered in our simulations is, compared to a primary forest, relatively young and still has significant potential for tree growth. Eventually the unmanaged forest turns into a carbon source and in our results, this is about at year 100. For different starting condition of the forest or different climate conditions, the timing may be different. Thus, we cannot conclude that an unmanaged forest is the better option for the next 100 years. This is supported by simulations of the unmanaged forest exhibiting different trajectories under three different climate scenarios (current, RCP 4.5 and RCP 8.5 in Fig. 5). The unmanaged forest reaching steady-state and thus being climate-neutral, takes about 250 years, according to our simulations. Literature to compare with our results is scarce. A study considering entire Austrian forests and using a different forest growth model (BFW 2020, Weiss *et al*. 2020), report that reference management after about year 2110 has similar or higher carbon sink, than a scenario with reduced wood harvesting. Forest carbon stocks reach a maximum between 2120 and 2140, similar to our results, noting that the considered management varies between this study and the cited literature.

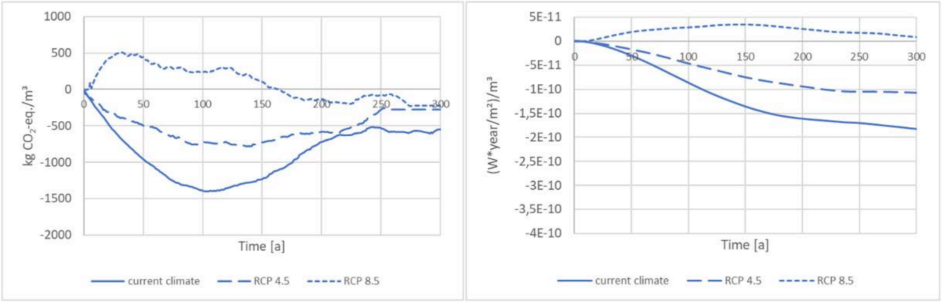

*Figure 5: Cumulative CO2 flux (left) and radiative forcing (right) of an unmanaged forest under different climate scenarios related to 1 m³ sawnwood.*

Abbildung 5: Kumulativer CO2 Fluss (links) und Strahlungsantrieb (rechts) eines unbewirtschafteten Waldes mit verschiedenen Klimaszenarien in Relation zu 1 m³ Schnittholz.

Our results suggest significant uncertainty in the carbon balance of forests especially when unmanaged. Thus, we cannot make generally valid conclusion on, whether managed or unmanaged forests perform better regarding their climate impact.

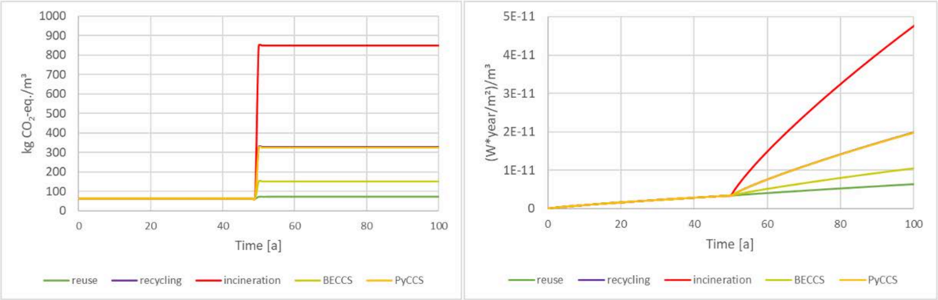

*Figure 6: Cumulative CO2 flux (left) and radiative forcing (right) of 1m³ sawnwood production with singular EoL scenarios.*

Abbildung 6: Kumulativer CO2 Fluss (links) und Strahlungsantrieb (rechts) von 1 m³ Schnittholzproduktion mit einmaligen EoL Szenarien.

Reuse is the most favourable EoL option as no carbon sequestered in the product is released to the atmosphere and only very few additional impacts (mainly transportation) are created by the process (Fig. 6). Recycling, which is not visible in the figure as the values coincidentally are nearly identical to PyCCS and therefore concealed, also releases no carbon from the product itself. However, the impacts related to the recycling process are significantly higher than for reuse and thus lead to a higher cumulated radiative forcing after 50 years. For the thermal processes the BECCS scenario, with an assumed 90% reduction in direct emissions, performs better than PyCCS with both PyCCS and BECCS outperforming state-of-the-art incineration, where the whole carbon from the product is released as $CO_2$ (along with other GHGs).

This trend is also visible in Figure 7, where an additional incineration scenario after 100 instead of 50 years was introduced. While in the long-term this scenario gets outperformed by BECCS and PyCCS, it is notable that the prolonged lifespan does, quite expectedly, lead to a lower radiative forcing until year 100. In turn improvements compared to the status quo can be achieved both through new technologies as well as different systemic approaches.

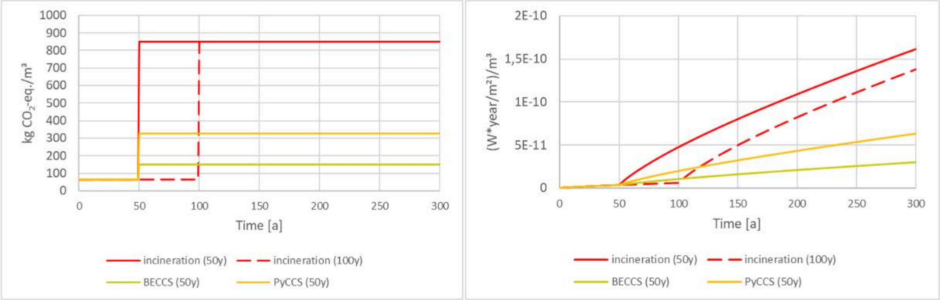

*Figure 7: Cumulative CO2 flux (left) and radiative forcing (right) of 1m³ sawnwood production with different thermal EoL scenarios.*

Abbildung 7: Kumulativer CO2 Fluss (links) und Strahlungsantrieb (rechts) von 1 m³ Schnittholzproduktion mit verschiedenen thermischen EoL Szenarien.

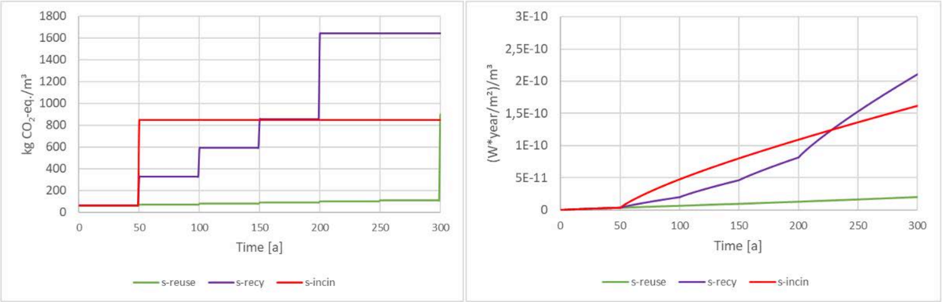

*Figure 8: Cumulative CO2 flux (left) and radiative forcing (right) of 1m³ sawnwood production with different EoL systems: reuse every 50 years with incineration in the year 300 (s-reuse), recycling in years 50 and 100 with incineration in the year 150 (s-recy), incineration after 50 years (s-incin).*

Abbildung 8: Kumulativer CO2 Fluss (links) und Strahlungsantrieb (rechts) von 1 m³ Schnittholzproduktion mit unterschiedlichen EoL Szenarien: Wiederverwendung alle 50 Jahre mit thermischer Verwertung im Jahr 300 (kurz: s-reuse), Recycling in 50 und 100 Jahren mit thermischer Verwertung im Jahr 150 (s-recy), thermische Verwertung nach 50 Jahren (s-incin).

While the short-term trends (reuse > recycling > incineration) are expected based on the previously presented numbers (Fig. 6 and 7), it is noteworthy that after year 225 the incineration scenario gets by-passed by recycling scenario in regard to the cumulative radiative forcing (Fig. 8). Multiple recycling cycles with subsequent incineration might not be a sustainability-wise feasible solution. However, we note that the function provided by these two scenarios is not identical and therefore a direct comparison is somewhat unreasonable. While in the recycling scenario the product (along with its functions) is available for 150 years, this is not the case in the incineration scenario. Here, an additional product would need to be produced in the year 50 and assuming again a lifetime of 50 years (incl. incineration) also in the year 100 to achieve the same function for the same timeframe.

Schematic results for the combination of both model components (forest managed with clear cut and product is sawnwood) are shown in Figure 9. Compared to the current approach of carbon neutrality the dynamic approach offers a more diverse picture. The impacts related to the sawnwood production are compensated after approx. 35 years when looking at the carbon balance itself. It takes about 60 years for the cumulative radiative forcing of the whole system to become negative. This reiterates the point that a long lifetime of products coupled with sustainable forest management are needed for climate-friendly wood construction systems.

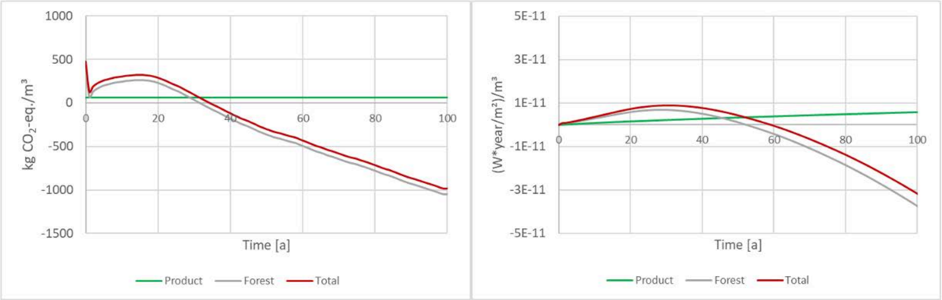

*Figure 9: Cumulative CO2 flux (left) and radiative forcing (right) of 1 m³ sawnwood production obtained from a clearcut.*

Abbildung 9: Kumulativer CO2-Fluss (links) und Strahlungsantrieb (rechts) von 1 m³ Schnittholzproduktion aus einem Kahlschlag.

## 4 Conclusion

This study shows, that using wood in long lasting timber building products can contribute to tackle climate change. Due to the persistence of GHGs in the atmosphere, the impact on the climate is more positive, if emissions are avoided earlier. Several carbon capture and storage as well as carbon usage methods currently being explored consider the effect of delayed emissions by long lasting timber products storing carbon and avoiding fossil GHG emissions, including that of cement or steel production.

To maximize the impact of such activities it is important to extend the RSL of wood products by reusing or recycling, which avoids releasing $CO_2$ in the atmosphere at

EoL, for instance by pyrolysis or CCS. Application of pyrolysis and use of charcoal added to soil to ensure storage of carbon in a stable form, can make it potentially carbon negative as $CO_2$ sourced from the atmosphere goes into the process of photosynthesis for plant growth (Gahane *et al*. 2022).

We note, that the impact of climate change on forestry cannot be predicted properly, since it depends on the forest conditions, the environmental conditions and forest management. The outcomes of applying the here outlined methodology for different forest stands (*e.g*. dominated by broadleaf tree species, younger or older stands) may deviate from the findings of our study considering an even-aged coniferous forest stand about 80 years old. Similar to climate scenarios providing possible climate conditions in the futures, results of dynamic LCAs of wood products can help to outline possible scenarios on the alternative products, forest management and wood utilization. Further research could expand the here outlined dynamic approach to entire buildings. This would provide the opportunity to compare the climate effectiveness of different building products and the impact of their related GHG emission points in time.

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