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Forest-based climate change mitigation

Towards improved climate impact assessments of forest-based systems

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Cover: Forest-based system perspective across time
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To those who have shared my path but had to go before.

Wege entstehen dadurch, dass man sie geht.

- Franz Kafka

Forest-based climate change mitigation

Abstract

The forest-based sector plays a crucial role in contributing to urgently required climate change mitigation. To assess this mitigation potential, a system perspective is required. This accounts likewise for the biogenic carbon balances of forests and wood products, as well as for the fossil greenhouse gas emissions of the forest value chain, and those emissions avoided from replaced products, i.e., substitution effects. However, within a system perspective of the forest-based sector, great spatial and temporal complexity, feedback effects and trade-offs exist among possible mitigation measures. This thesis aims at improving the understanding of climate impacts in the forest-based sector from a system perspective to support more effective design of climate change mitigation measures. To that end, four forest-based systems were analyzed across different scales (product vs. market scale) and assessment approaches (supply-driven vs. demand driven) by integrating forest modelling data and life cycle assessment methodology. The overall results indicate that methodological decisions, especially assessment scale and approach, highly influence the estimated climate impact. Within a system perspective, the forest carbon sink has the most important contribution for climate change mitigation. Substitution effects can be misjudged if a supply-driven assessment approach is applied, while a demand-driven approach ensures a more realistic estimation. Future climate impact assessments from a system perspective should focus first on the question of which societal functions (e.g. housing) can expect which demand projection, and second, what role wood can play to fulfil the functions. Only after that should possible substitution effects be calculated, followed by estimating changes in the stored biogenic carbon in wood products, and lastly, the alteration of the forest carbon sink.

Keywords: forest-based sector, climate change mitigation, substitution effect, life cycle assessment, forest management, timber construction, paper recycling, bioeconomy

Skogsbaserad begränsning av klimatförändringar

Sammanfattning

Skogssektorn spelar en viktig roll i den nödvändiga begränsningen av klimatförändringarna. För att bedöma dess betydelse krävs ett systemperspektiv. Detta tar lika stor hänsyn till skogens upptag av koldioxid, lagring av biogent kol i träprodukter och fossila växthusgasutsläpp i skogsbrukets värdekedja samt de utsläpp som undviks genom ersättningsprodukter, vilket kallas substitutionseffekten. Ett systemperspektiv för skogsbrukssektorn medför dock komplexitet som återkopplingseffekter och avvägningar mellan möjliga åtgärder för att begränsa klimatförändringarna. Syftet med den här avhandlingen är att fördjupa kunskapen för den skogsbaserade sektorns klimatpåverkan ur ett systemperspektiv för att möjliggöra en mer effektiv utformning av åtgärder för att begränsa klimatförändringarna. För detta ändamål analyserades fyra skogsbaserade system på olika skalor (produkt- och marknadsskala) och angreppssätt (utbudsorienterad och efterfrågeorienterad) med hjälp av skogsmodelleringsdata och livscykelanalys. Resultaten visar att metodmässig beslut, särskilt när det gäller bedömningsskala och angreppssätt, har stor inverkan på beräknade klimatpåverkan. Ur ett systemperspektiv är det skogens kolupptag som ger det viktigaste bidraget för att motverka klimatförändringen. Substitutionseffekter kan missbedömas när man tillämpar en utbudsorienterad analys, medan en efterfrågeorienterad metod säkerställer en mer realistisk bedömning. Framtida klimatkonsekvensbedömningar av skogsbrukssektorn bör först undersöka vilka funktioner (t.ex. bostäder) som förväntas uppfylla vilken efterfrågeprognos och vilken roll trä kan spela för att uppfylla dessa funktioner. Därefter bör eventuella substitutionseffekter beräknas, följt av en uppskattning av det lagrade biogena kolet i träprodukter och slutligen förändringen av skogens kolupptag.

Keywords: skogssektor, begränsning av klimatförändringar, substitutionseffekt, livscykelanalys, skogsbruk, träkonstruktion, pappersåtervinning, bioekonomi

Forstbasierter Klimaschutz

Zusammenfassung

Der Forstsektor spielt eine wichtige Rolle bei der erforderlichen Eindämmung des Klimawandels. Um diese Rolle zu bewerten ist eine Systemperspektive erforderlich. Diese berücksichtigt gleichermaßen die Bindung von Kohlenstoffdioxid im Wald, die Speicherung von Kohlenstoff in Holzprodukten, die fossilen Treibhausgasemissionen der forstwirtschaftlichen Wertschöpfungskette und die fossilen Emissionen, die durch ersetzte Produkte vermieden werden, was als Substitutionseffekt bezeichnet wird. In einer Systemperspektive des Forstsektors verursachen Komplexität und Rückkopplungseffekte jedoch Zielkonflikte zwischen möglichen Klimaschutzmaßnahmen. Ziel dieser Arbeit ist es, das Verständnis der Klimaauswirkungen des Forstsektors aus einer Systemperspektive zu verbessern, um eine effektivere Gestaltung von Klimaschutzmaßnahmen zu ermöglichen. Zu diesem Zweck wurden vier forstbasierte Systeme auf verschiedenen Skalen (Produkt- und Marktskala) und Bewertungsansätzen (angebotsorientiert und nachfrageorientiert) mittels Waldmodellierungsdaten und Ökobilanzmethoden analysiert. Die Ergebnisse zeigen auf, dass methodische Entscheidungen die berechneten Klimaauswirkungen stark beeinflussen. Aus einer Systemperspektive betrachtet leistet die Kohlenstoffsenke des Waldes den wichtigsten Klimaschutzbeitrag. Substitutionseffekte bergen das Risiko einer Fehleinschätzung unter Anwendung einer angebotsorientierten Analyse, während ein nachfrageorientierter Ansatz eine realistischere Bewertung gewährleistet. Zukünftige Klimafolgenabschätzungen des Forstsektors sollten zunächst untersuchen welche Funktionen (z.B. Wohnen) welche Nachfrageprognose erwarten lassen und welche Rolle Holz bei der Erfüllung dieser Funktionen spielen kann. Erst dann sollten mögliche Substitutionseffekte berechnet werden, gefolgt von der Abschätzung des gespeicherten biogenen Kohlenstoffs in Holzprodukten und schließlich der Veränderung des Waldkohlenstoffs.

Keywords: Forstsektor, Klimaschutz, Substitutionseffekt, Ökobilanz, Waldbewirtschaftung, Holzbau, Papierrecycling, Bioökonomie

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Schulte, M., Hammar, T., Stendahl, J., Seleborg, M., & Hansson, P.-A. (2021). Time dynamic climate impacts of a eucalyptus pulp product: Life cycle assessment including biogenic carbon and substitution effects. *Global Change Biology Bioenergy*, 13, pp. 1831-1850, https://doi.org/10.1111/gcbb.12894

II. Schulte, M., Jonsson, R., Hammar, T., Stendahl, J., Hansson, P.-A., (2022): Nordic forest management towards climate change mitigation: time dynamic temperature change impacts of wood product systems including substitution effects. *European Journal of Forest Research*, 141, pp. 845–863, https://doi.org/10.1007/s10342-022-01477-1

III. Schulte, M., Jonsson, R., Eggers, J., Hammar, T., Stendahl, J., Hansson, P.-A., (2023): Demand-driven climate change mitigation and trade-offs from wood product substitution: The case of Swedish multi-family housing construction. *Journal of Cleaner Production*, 421, https://doi.org/10.1016/j.jclepro.2023.138487

IV. Schulte, M., Jonsson, R., Hammar, T., Eggers, J., Stendahl, J., Hansson, P.-A., (2024): Climate change mitigation from increased paper recycling in Sweden: Conserving forests or utilizing substitution? *Environmental Research Communications*, 6, https://iopscience.iop.org/article/10.1088/2515-7620/ad5930

Papers I-IV are reproduced with the permission of the publishers (open access).

The contribution of Maximilian Schulte to the papers included in this thesis was as follows:

I. Methodology, formal analysis, investigation, writing—original draft, writing – review & editing, visualization

II. Conceptualization, methodology, formal analysis, investigation, writing—original draft, writing – review & editing, visualization

III. Conceptualization, methodology, formal analysis, investigation, writing – original draft, writing – review & editing, visualization

IV. Conceptualization, methodology, formal analysis, investigation, writing – original draft, writing – review & editing, visualization

Abbreviations

ATF	Average timber frame
C	Carbon
CCF	Continuous cover forestry
CH_4	Methane
CHP	Combined Heat & Power
CLT	Cross-laminated timber
CO_2	Carbon dioxide
DF	Displacement factor
dLUC	Direct land use change
eq	Equivalent
EU	European Union
FRL	Forest reference level
GHG	Greenhouse gas
GWP	Global warming potential
ha	hectare
HDPE	High-density polyethylene
HVO	Hydrogenated vegetable oil
HWP	Harvested wood product
IAM	Integrated assessment model

iLUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
K	Kelvin
LCA	Life cycle assessment
LCI	Life cycle inventory
LULUCF	Land Use, Land Use Change & Forestry
m^2	Square meter
m^3	Cubic meter
MFHC	Multi-family housing construction
Mg	Megagram (1000 kg)
Mha	Million hectares
MMCF	Man-made cellulosic fiber
Mt	Million tons
N_2O	Nitrous oxide
NFI	National forest inventory
PET	Polyethylene terephthalate
PP	Polypropylene
ppm	Parts per million
PUR	Polyurethane
PVC	Polyvinylchloride
SFA	Swedish Forest Agency (Skogsstyrelsen)
SOC	Soil organic carbon
SSP	Shared socioeconomic pathway
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

Earth is beyond six of the nine planetary boundaries which describe the critical processes for maintaining the stability and resilience of the Earth system as a whole (Rockström et al. 2009; Richardson et al. 2023). Among these planetary boundaries, climate change is identified as one of two "core boundaries" based on its fundamental importance for the Earth system (Steffen et al. 2015). In 2023, human-induced climate change has increased the Earth's surface temperature by 1.45°C relative to preindustrial times (WMO 2024). This global warming is principally caused by the continuous emission of greenhouse gases (GHGs) from the use of fossil energy sources, the production and consumption of materials, as well as by land use and land use change. Climate change has detrimental impacts on food and water security, human health, natural ecosystems, economies, and societies worldwide. These impacts will persist for centuries to millennia and may continue to cause further long-term changes in the climate system. Mitigation of climate change is, therefore, urgently required to alleviate the consequences. In 2015, the Paris Agreement was adopted as a legally binding international treaty on climate change, aiming to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" (UNFCCC 2015). To mitigate climate change, two general methods exist. First, reducing GHG emissions to the atmosphere and second, removing them from the atmosphere.

The forest-based sector is considered to play a crucial role in contributing to climate change mitigation (IPCC 2023) next to its other provisioning services, such as the supply of renewable biological resources. On the one hand, forests remove greenhouse gases from the atmosphere by sequestering carbon dioxide (CO_2) through photosynthesis to store it as biogenic carbon in living biomass, soil organic carbon (SOC), and renewable wood products, retaining the CO_2 from the atmosphere. On the other hand, wood products have the potential to reduce overall emissions of fossil GHGs; wood products tend to emit fewer fossil emissions during their life cycle than equivalent products from non-wood materials, such as concrete or plastics, which fulfill the same function. A verifiable replacement of non-wood products by wood products which serve the same function can reduce the net quantity of GHGs emitted to the atmosphere, which is referred to as substitution effect. However, trade-offs exist among forest-based strategies to mitigate climate change. This is foremost because increasing carbon storage in wood products and enhancing the substitution effect by harvesting more wood conflicts with fostering the forest carbon sink (Soimakallio et al. 2021). But trade-offs also entail compromises between climate change mitigation and other environmental goals, e.g., connected to biodiversity (Mazziotta et al. 2022).

In the European Union (EU) the forest-based sector is considered a key pillar in climate change mitigation strategies (EC 2023). Several EU level regulations have thus imbedded the contribution of forests and wood products to counteract global warming. Within the EU, Sweden has the largest forest area with about 28 million (M) ha, is the second largest wood supplier (Eurostat 2024), and aims to be one of the world’s first fossil-free welfare states with no net GHG emissions by 2045 (Ministry of Infrastructure of Sweden 2020). Alongside this, Sweden is at the forefront in terms of wood-based construction and when it comes to the recycling of wood-based products. Climate programs at the EU level relating to forests and wood products therefore have great relevance for Swedish forests and the national forest-based sector. Likewise, Swedish forests and the national forest-based sector are key to meeting national and EU climate targets. This has sparked great interest as to how the Swedish forest-based sector can improve climate change mitigation, especially concerning the aforementioned trade-offs. In this context, many questions have been raised which bear special relevance for the structure and characteristics of both the Swedish and the general forest-based sector:

What are the climate effects of changing forest management practices?

What are the climate effects of using a wood-based product over a fossil-based alternative?

What are the climate effects of replacing mineral-based construction materials with wood alternatives in the housing sector?

What are the climate effects of increased paper recycling?

Answering these questions requires climate assessments characterized by temporal and spatial diversity, complexity, and feedback effects, as they all represent different systems within the forest-based sector (Hetemäki and Kangas 2022; Rüter 2023). These climate assessments need to involve a broad range of processes among the ecosphere and technosphere simultaneously. Furthermore, the climate assessments can take place on different scales, 'product scale' or 'market scale', and the approach can be either 'supply-driven' or 'demand-driven'.

On the product scale a single function is assessed, for which often a finished wood product is used instead of a counterpart product, such as in Hammar et al. (2015) or Andersen et al. (2021). On the market scale, multiple functions are assessed, for which often only semi-finished wood products are used instead of counterpart products, as done in, for example, Petersson et al. (2022). Product or market scale assessments can be conducted using either a supply- or demand-driven approach. In the supply-driven approach, the quantity of the wood product(s) fulfilling one or multiple function(s) are controlled by additional supplies originating from activities either in the forest (Skytt et al. 2021), or along the forest value chain (Suter et al. 2017). In the demand-driven approach, the quantity of the wood product(s) fulfilling one or multiple function(s) are steered by additional demand for the functions with possible implications for the value chain and the forest (Hafner and Rüter 2018).

Many climate impact assessments of the forest-based sector have been conducted across the abovementioned scales and approaches. And yet, this variety still frequently impedes unambiguous recommendations for clear and effective climate change mitigation. Therefore, a system perspective is required in assessments analyzing effective mitigation measures for policies aiming towards climate neutrality (Nabuurs et al. 2007; EC 2021a). This requires the simultaneous inclusion of: (1) biogenic carbon balances in forests and (2) wood products, as well as (3) fossil GHG emissions along the forest value chain, and (4) the substitution effect. This is necessary to capture the abovementioned complexity, and feedback effects within forest-based systems.

Indeed, a consistent system perspective including consideration of these four components of a forest-based system is sometimes missing in climate impact assessments (Judl et al. 2011; Smyth et al. 2017; Brunet-Navarro et al. 2021). However, even if a system perspective may be given, the understanding of differences as to the climate effects across either the product or market scale, and along either a supply- or demand-driven approach, still requires improvements for better targeted mitigation policies. In order to increase this understanding, additional research is required. Research which enhances knowledge for designing effective climate change mitigation measures of forest-based systems. This is where the present thesis departs.

2. Aim and structure

2.1 Aim and objectives

The overall aim of this thesis is to improve the understanding of climate impacts of the forest-based sector from a system perspective to support effective design of climate change mitigation measures.

The specific objectives are to:

- Assess the contribution and magnitude of the forest carbon sink, HWP carbon storage, and fossil GHG balances from a system perspective on the product scale (Paper I, III, IV) and market scale (Paper II),
- Analyze the impact of a supply- (Paper I, II, IV) or demand-driven (Paper III) assessment approach from a system perspective,
- Enhance knowledge as to the climate effects' magnitude, origin, temporal dynamics, and general trade-offs as a consequence of changing forest management (Paper II) or upscaling wood use in multi-family housing construction (Paper III),
- Investigate effective climate change mitigation measures resulting from efficiency gains in the forest-based sector in the form of increased paper recycling (Paper IV).

2.2 Research structure

This thesis comprises the work of Papers I-IV (Figure 1), each analyzing forest-based climate impacts from a system perspective on a product or market scale following either a supply- or demand-driven modelling approach (compare Section 3.2.5).

Paper I and Paper II formed the basis for the overall modelling framework. In both Papers, the modelling followed a supply-driven approach. The analysis departed from the forest and led to the provision of supplied wood products fulfilling either one (Paper I) or several (Paper II) functions, while the remaining system, including storage of biogenic carbon in wood products and fossil GHG balances, was modelled hereafter ('*forest to function*'). Paper I exemplified this at the product scale along the life cycle of one particular wood use, a beverage carton sourced from Eucalyptus pulp, which, due to its supply, was assumed to replace a PET bottle in fulfilling the function of 'a beverage container' including the sourcing of the resources, processing, and end-of-life use. In Paper II, the assessment was set at the market scale and integrated a biophysical Swedish forest model which simulated forest development and wood supply. The focus here was on climate effects of changing forest management in different regions across the country. Regional forest modelling was performed, and a portfolio of wood products was modelled to replace respective non-wood products for a variety of functions.

Paper III switched the modelling sequence applied in Paper I and Paper II so that the analysis departed from the demand for a single function (product scale) which either wood or alternative materials can fulfill. This function was the 'living area' in the projected national Swedish multifamily housing construction, for which, hitherto, concrete serves as the dominant frame material. In a scenario, this concrete frame dominance switched to a permanent timber frame dominance by 2030. First, implications for forest value chain emissions and substitution effects, as well as additional carbon storage in wood products, were assessed, and only after that the consequences for the forest carbon sink ('*function to forest*'). Changes in the fossil GHG and biogenic carbon balances were thus primarily steered by demand.

Paper IV ascertained potential climate change mitigation options through an increase in the Swedish paper recycling rate to a theoretical maximum.

The general modelling sequence was supply-driven, yet the additional supply of wood did not originate in the forest but from within the forest value chain in the form of additional recovered pulp from increased paper recycling. From that, the modelling extended over changes as to the forest carbon sink, or implication for fossil GHG balances, respectively - depending on the climate change mitigation strategy (‘*fiber to forest or function*’). Two strategies were ascertained, either extending conservation of forests or utilizing substitution effects.

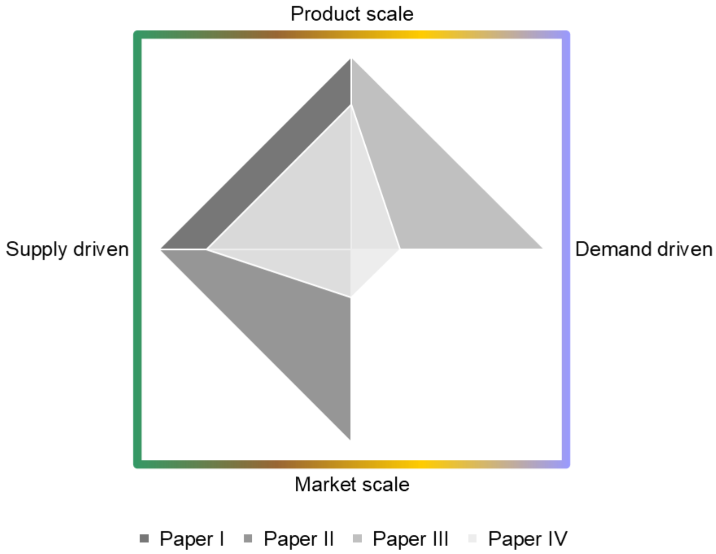

Figure 1 Conceptual framework of Papers I-IV included in this thesis. The colored frame represents the system perspective assessing the climate effects of forest-based systems (compare Figure 2 & Figure 4). The forest is represented in green, the wood products in brown, the forest value chain in yellow, and substitution effects in purple. Each Paper is represented by a triangle (Papers I-III) or an overlying trapezoid (Paper IV), and lies within the system perspective, i.e., all four components are considered in each assessment. In Paper I and II, the assessment approach is supply-driven, departs in the forest and ends with modelling the substituted function for which wood may be used (‘*forest to function*’). In Paper III, the assessment approach is demand-driven as it starts with the foreseen demand of a function, for which wood can substitute the currently dominating alternative, and ends with the implications for the forest (‘*function to forest*’). Paper I and III rely on a product scale, i.e., they assess only the climate effects for a single function, respectively. Paper II, in contrast, is set at the market scale, as it includes a portfolio of various wood uses to fulfill various functions. The modelling of Paper IV is a hybrid version as it has characteristics of both, a product- and market scale, and follows a supply-driven assessment approach and also assesses aspects considering the demand of the wood products under study (*‘fiber to forest or function’).*

2.3 Thesis structure

In the following, Section 3 describes the principal research themes of Papers I-IV, their state of knowledge as well as methods, research gaps, and relevance for climate change mitigation policies. Thereafter, Section 4 explains how the research themes described in Section 3 were applied in Papers I-IV. Section 5 continues by presenting the main research findings of Papers I-IV and discussing them. Section 6 enters a more general discussion of the research and the overarching findings of this thesis in terms of the applied methods and modelling approaches. Section 7 summarizes the conclusions of the thesis. Finally, Section 8 proposes where future research should focus within the research field.

3. Theoretical background

3.1 Climate change and climate change mitigation

The sun’s incoming short-wave solar radiation arrives as light energy on the Earth’s surface. One part is taken up by the Earth’s surface in the form of heat and the rest is reflected as long-wave heat radiation back into the atmosphere and, thereafter, into space (IPCC 2021). Greenhouse gases (GHGs) in the Earth’s atmosphere hinder a fraction of the outgoing long-wave radiation to exit into space (IPCC 2021). Instead, parts of the radiation are reflected back on the Earth’s surface, resulting in yet another heating: the greenhouse effect. Thanks to the greenhouse effect, the global mean temperature has developed over millennia to create a climate that allowed ecosystems to thrive in a way which enabled humans to create civilizations, societies, and economies to the extent they exist today.

The difference between incoming and outgoing radiation is understood as radiative forcing and is measured in $W\ m^{-2}$. Radiative forcing is influenced by GHGs, where the more GHGs there are, the more radiative forcing there is, which itself leads to rising global temperatures (IPCC 2021). Carbon dioxide (CO_2) is the most important anthropogenic GHG, next to methane (CH_4), and nitrous oxide (N_2O). These persist in the atmosphere over decades to millennia unless they are sequestered by vegetation via photosynthesis or taken up by the oceans. CO_2 is the most important of all GHGs due to its dominance in emission quantities (IPCC 2021). An important characterization frequently made with respect to atmospheric CO_2 is to distinguish between fossil CO_2 and biogenic CO_2, with the former originating from fossil resources used for energy or material purposes, and the latter from biomass and soils. Physically though, no difference exists between a biogenic or fossil CO_2 molecule, both influence the radiative forcing to the same degree.

Today, in the year 2024, the concentration of GHGs has reached an unprecedented peak, with CO_2 at 420 ppm compared to approximately 280 ppm before 1750, which has caused global warming to reach 1.1°C compared to pre-industrial times (IPCC 2023). On a global scale, the emissions of GHGs are continuously increasing which further exceeds the planetary boundary of climate change (Steffen et al. 2015; Richardson et al. 2023). Moreover, this risks jeopardizing the Paris agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC), which aims to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” (EU 2023). With consequences of global warming being increasingly apparent in the form of, for example, more frequent meteorological extremes such as storms, droughts, heavy precipitation, or flood occurrences, the mitigation of global warming is imperative to reduce risks of strongly exacerbating ecological harm, societal drawbacks, and economic damage (IPCC 2023).

The European Union (EU) has set ambitious targets to reach the goal of the Paris agreement in the form of the European Green Deal (EC 2023). Until 2030, a reduction of 55% in GHG emissions is required (‘Fit for 55’), with a goal of climate neutrality by 2050 (European Council 2023; EC 2023). One important pillar for reaching these targets is the EU’s Land Use, Land-Use Change, and Forestry (LULUCF) sector, which includes forests and wood products, as well as other land uses. In 2021, EU forests and wood products removed approximately 320 Mt CO_2 equivalent (eq), which was offset to a net sequestration of 230 Mt CO_2 eq by emissions from other land uses (settlements, cropland, etc.) (EEA 2023a). This net sequestration of the LULUCF-sector compensates for about 7% of the EU-27’s total emission of GHGs (EEA 2023b). Consequently, the European Green Deal relies to a considerable degree on forests and forestry to achieve EU climate neutrality by 2050.

Sweden, as part of the EU, strives to become the first climate neutral welfare state by 2045 (Ministry of Infrastructure of Sweden 2020). This requires substantial efforts to reduce total GHG emissions from the current 48 Mt CO_2 eq as of 2021 (SCB 2023). Of all the EU countries, Sweden hosts the largest forest area (Eurostat 2024) and the national contribution to the net sequestration of the EU LULUCF-sector amounts to about 19% (SEPA

2023; EEA 2023a). Sweden and its forest-based sector therefore play a substantial role in reaching climate neutrality in the EU and thus in contributing to the Paris Agreement. To tackle global warming and reach the given climate targets, the two general measures are either the reduction of GHG emissions to the atmosphere or an increase in their removal from the atmosphere – two measures for which the forest-based sector has the potential to contribute.

3.2 Forest-based climate change mitigation

In the context of forest-based climate change mitigation and associated assessments, the forest-based sector and parts thereof can be defined by forest-based systems. Figure 2 illustrates a forest-based system and its four components, divided into the ecosphere, and the technosphere (i.e., the part of the environment made or modified by humans). The four components are: firstly, forests as both natural carbon sinks and sources being part of the land-based ecosphere; secondly, wood products and their capacity to retain carbon over their lifespan with eventual release; thirdly, the value chain of the forest industry and its fossil GHG emissions, for example, along sawmills or pulp mills; and finally, substitution (i.e., potentially replacing non-wood products such as concrete, steel, or plastics, and the associated avoided fossil GHG emissions). To understand the net climate impact of a forest-based system, the biogenic carbon dynamics in forests and wood products, as well as fossil GHG dynamics, along the value chain must be added, while the avoided fossil GHG emissions from substitution must be subtracted. This simultaneous consideration of the four components of forest-based systems in climate impact assessments is understood as a ‘system perspective’ (EC 2021a; Nabuurs et al. 2007). Despite increasing the complexity and associated uncertainty of a climate impact assessment, a system perspective is considered to provide a sound basis for robust decision making (Cowie et al. 2021). The definition of a system perspective is further explained in Section 3.2.5. This understanding of a forest-based system in the context of climate change mitigation is used in this thesis.

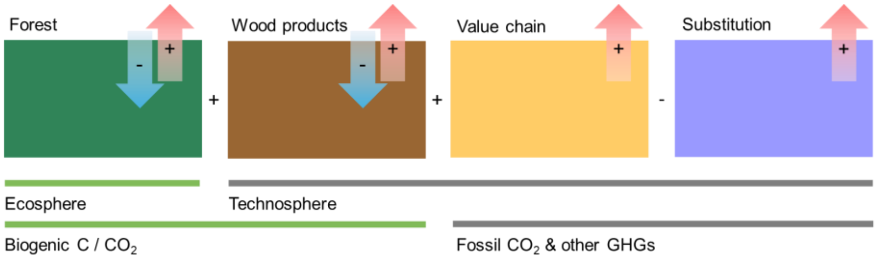

Figure 2 Framework for a climate impact assessment of a forest-based system including the components of a system perspective: forest, wood products, value chain, and substitution, as well as the relevant greenhouse gases and their attribution to the eco- or technosphere, respectively. Note: C = carbon, CO_2 = carbon dioxide, GHGs = greenhouse gases.

Great spatial and temporal complexity, feedback effects, trade-offs and synergies exist among the four components of a system perspective in the context of climate change mitigation (EC 2021a; Jonsson et al. 2021; Hetemäki and Kangas 2022). For example, trade-offs are given between increasing carbon stocks in forests, and harvesting more wood for additional substitution. A synergy, on the other hand, can emerge when harvesting is increased, as the carbon storage in HWP increases as does the potential for substitution effects. It is thus acknowledged by several political and research strategies that only overarching, simultaneous consideration of these components can generate effective climate change mitigation measures (Nabuurs et al. 2018; Verkerk et al. 2022; EC 2021a). Meanwhile, omitting one or more of the components, such as forest carbon (Smyth et al. 2017; Brunet-Navarro et al. 2021) and wood product carbon storage (Judl et al. 2011), or substitution (Lan et al. 2020), can lead to an incomplete assessment, risking misjudging of the net implications for the climate.

Table 1 elaborates on the temporal and spatial complexity of mitigation options among the four components. In terms of the forest, albedo (i.e., the reflection of solar radiation) and aerosols add to the biophysical impacts from biogenic carbon which can be altered, for example, through forest management. Forest disturbances impact the mitigation options alongside this. Forest management aiming for more resilient forests, for example, through changing tree species or increasing shares of mixed forests, can reduce susceptibility to forest disturbances and thus help to maintain a healthy forest ecosystem for effective mitigation. In terms of wood product carbon storage, the principle of cascading (i.e., re-use) of wood can extend the retention of carbon from the atmosphere and thus increase mitigation potentials. This can also have a direct impact on fossil emissions along the value chain of the forest industry. Here, innovation and increasing efficiency in production processes, or regarding end-of-life management, can be introduced, such as shifting from energy recovery to material re-use of a certain wood product. Likewise, these measures can also be accounted for with replaced products and their fossil emission profiles, which affect the degree of substitution. Finally, socioeconomic and political impacts can, via feedback effects, influence the overall development of forest carbon or fossil value chain emissions, for example, through updated LULUCF-requirements, or legally binding decarbonization commitments affecting the value chains of the forest industry and those being substituted.

In the following, a more detailed description and explanation of the four components of a system perspective - forests, HWPs, forest value chain, substitution is given. Afterwards, the assessment scales are described in greater detail, as well as the distinction between a supply-, and demand-driven assessment approach. Alongside a general description of each concept, the focus is - where suitable - put on climate change mitigation relevance from an EU and Swedish perspective.

Table 1 Forest-based climate change mitigation options and examples (adapted from Hetemäki and Kangas (2022))

Mitigation option	Example
Forest	
Forest carbon sequestration in trees and soils (forest carbon sink)	Stop deforestation, increase afforestation and reforestation, increase tree growth, reduce harvest levels.
Forest albedo	Change from coniferous forest to broadleaved or mixed forest.
Forest aerosols	Afforestation and conserving forests.
Forest disturbances	Forest adaptation towards changing climate and more resilience, e.g., by changing tree species, or increasing share of mixed forests.
Wood products	
Carbon storage in wood products	Increase the share of long-lived wood products.
Cascading wood use	Re-use of wood products for another purpose to extend the time of carbon retention.
Value chain	
Production, efficiency, and logistics	Reduce or abolish the use of emission intensive fuels and products along the forest value chain, e.g., in transport, or energy generation (decarbonization).
Substitution	
Substituting wood products for more emission-intensive materials, energy, and products for fulfilling the same function	Increase demand for wood-based products and warrant real avoidance of producing the replaced product. Develop new wood product alternatives.
Socioeconomic and political impacts	
Trade-offs or synergies between the mitigation options and other societal objectives	Leakage impacts, political support for mitigation measures, biodiversity impacts, income, and employments impacts.

3.2.1 Forest

Globally, forests act as the dominant land-based carbon sink with approximately 3,500 Mt C yr^{-1} during 1990-2020 (Pan et al. 2011; Pan et al. 2024). In addition, they provide the largest supply of renewable biological resources not competing with food production (unlike agricultural land) (Hetemäki and Kangas 2022). Forests grow and sequester atmospheric CO_2 via photosynthesis in their biomass, and root turnover transforms the sequestered carbon into the soil. Moreover, forests maintain biogenic carbon in dead wood, from where it is successively released into the atmosphere. Large spatial variations exist among forest resources in terms of growth, species, or age, which are dependent on abiotic factors, such as climate, precipitation, or soil conditions, and biotic factors, such as tree density, tree species richness, or canopy cover. The climate effects of forests can thus differ greatly across space and time, so climate impact assessments of forest carbon balances can result in various outcomes. The relevant data of biogenic carbon fluxes can be sourced from on-site measurements, or, for example, from biophysical forest models processing forest inventory data with underlying growth or mortality functions. An overview of different forest models and their functioning is further given in Section 3.4. Moreover offers remote sensing increasing possibilities to measure the carbon stock changes (Du et al. 2023).

The New EU Forest Strategy for 2030 and the EU Soil Strategy for 2030 recognize the need to protect and improve the quality of forests and soil ecosystems to enhance carbon sequestration and strengthen the resilience of forests and soils against climate and biodiversity crises (EC 2021b). As stated above, the regulation on the LULUCF-sector sets out how land use, and thus forests, contribute to the EU's climate goals, such as those under the European Climate Law (EC 2023). The LULUCF regulation was revised in 2023 for the period up to 2030 with the target of contributing to a net carbon removal of 310 Mt CO_2 eq $year^{-1}$ by 2030 (EU 2018, 2023). To reach the target, large additional efforts are required to further the current net biogenic carbon sink (230 Mt CO_2 eq $year^{-1}$ as of 2021) (EEA 2023a), for which European forests play the largest role as their sequestration (280 Mt CO_2 eq $year^{-1}$ as of 2021) largely offsets the emissions from, for example, the agricultural sector. This requirement is exacerbated because the EU forest sink has clearly moved in the opposite direction for years. Instead of an increasing net sink, it is progressively moving away from the LULUCF target for 2030 - likely a continuing trend unless current management practices change rapidly (Korosuo et al. 2023).

Sweden hosts the largest forest area in the EU with 28 million (M) ha and is its second largest wood supplier (Eurostat 2024) based on decades of active forest management chiefly via clear-cut harvesting practices (Lundmark et al. 2013; Lundmark et al. 2014). The country has one of the largest LULUCF Member State contributions, which amounts to 39 Mt CO_2 eq year^{-1} based on the national forest reference level (FRL) from 2021-2025, a projected country-level benchmark of net forest emissions against which future net emissions are compared (Vizzarri et al. 2021). However, after about a century of increase, forest growth, and thus forest carbon sequestration, has abruptly decreased over the last decade in Sweden, with climate related drought being the most likely reason behind this (Laudon et al. 2024). This aggravates the efforts needed to reach the Swedish net sink by 2030, amounting to about 43 Mt CO_2 eq year^{-1} (EU 2023) if this trend continues. To reach the target, i.e., an additional 4 Mt CO_2 eq year^{-1} by 2030 (the largest Member State LULUCF target), Sweden's forests will provide the most important contribution. Multiple means are proposed in this context by the Swedish Forest Agency (SFA). These encompass extending rotation times, decreasing harvest levels, increasing forest set-aside areas, using improved tree seedlings, changing tree species selection (e.g., spruce to birch), switching from clear-cut forest management towards continuous cover forest management, increasing forest fertilization with nitrogen, or reducing browsing damages (SFA 2023).

3.2.2 Wood products

Wood products, or harvested wood products (HWPs), store the biogenic carbon formerly present in trees, keeping it from the atmosphere and thus contributing to climate change mitigation (IPCC 2023). The transfer of carbon from trees to HWPs is similar to when biogenic carbon is transferred from aboveground biomass to litter and SOC, although the transfer from vegetation to HWPs is always based on anthropogenic activity (technosphere).

In the context of assessing the climate role of wood products, the biogenic carbon pool therein and the fluxes in and out of that pool need to be defined.

The HWP pool represents the sum of all biogenic carbon being stored at a given point in time. The production of new wood products leads to an inflow to the HWP biogenic carbon pool, and an outflow is created when wood products reach the end of their life and are burned or decompose. Depending on the balance between carbon inflow and outflow, the HWP biogenic carbon pool can be either a sink or a source of biogenic CO_2. Socioeconomic factors, such as population growth, income, or trade, determine the amount of wood products being produced and consumed, and, thus, the carbon sequestration potential of the HWP pool on a regional or global scale (Johnston and Radeloff 2019). The composition of the wood product portfolio furthermore plays a crucial role for the HWP carbon sink.

In general, harvested wood (i.e., wood in the rough) is considered as either fuelwood, or divided into the assortments of sawlog or pulpwood, depending on the log diameter (FAO 2022). From here, a great variety of semi-finished HWPs is produced. Sawlogs serve as the origin for sawnwood and wood-based panels in the form of, for example, plywood, particleboard, or fiberboard. By-products from sawlog processing emerge as wood chips, and particles, sawdust, and sawnwood cutting residues, which may all be used for a variety of purposes, such as wood pellets. Pulpwood is used in pulp making, to produce either chemical, semi-chemical, mechanical, or dissolving pulp. Chemical pulp, semi-chemical pulp and mechanical pulp are used to produce paper and paperboard types, such as graphic papers, sanitary and household papers, or packaging papers. Dissolving pulp is, for example, used to produce man-made cellulosic fiber (MMCF), i.e., cellulose-based textile fiber such as viscose, or lyocell. Finally, wood recycling, in the form of, for example, paper recovery, yields recovered pulp which can serve as a substitute for virgin, or primary pulp.

Today, only limited knowledge exists for EU wood flows as to the purpose the semi-finished wood products are finally produced for. The hitherto established practices of assessing the climate effects of the HWP carbon pool are based on the semi-finished wood product level. This applies not only for Sweden (Skytt et al. 2021; Petersson et al. 2022) but also for assessments of Germany, Finland, France, or Spain (Bozzolan et al. 2024). This represents the potential for improvement, not only because the current and future contribution potential of the HWP carbon to climate change mitigation is mandatorily included within the current LULUCF reporting to the UNFCCC, based on the Intergovernmental Panel on Climate Change

(IPCC) *Good Practice Guidance* (Rüter et al. 2019). Here, a distinction is made among three semi-finished wood commodity classes: sawnwood, wood-based panels, paper and paperboard. Each of these semi-finished wood commodity classes is characterized by default half-life times, which describe the "the number of years it takes to lose one half of the material currently in the pool", or, in other words, the decay of the HWP commodity class and thus the intensity of the gradual loss of the retained biogenic carbon.

Table 2 summarizes the half-life times of sawnwood, wood-based panels, and paper and paperboard. For sawnwood, the default half-life time is 35 years, while that of wood-based panels and that of paper and paperboard is 25, and 2 years, respectively. Depending on the yearly decay of wood products and the consequential loss of biogenic carbon based on the half-life times, together with the annual inflow into the HWP pool, the effects on the carbon balance can be described in more detail by:

$$C_l(i+1) = e^{-k} \times C_l(i) + \left[\frac{\left(1-e^{-k}\right)}{k}\right] \times Inflow_l(i) \qquad (1)$$

where $C_l(i)$ is the carbon stock of a particular HWP commodity class *l* at the beginning of year i, given, for example in Mt C; k is the decay constant for each HWP commodity class *l* given in units years^{-1} (which is defined by the second natural logarithm, i.e., ln (2), divided by the half-life time of each HWP commodity class in the HWP pool in years, respectively); and $Inflow_l(i)$ is the carbon inflow to the particular HWP commodity class *l* during year i, given in, for example, Mt C year^{-1}.

The carbon stock change of a particular HWP commodity class *l* during the year i, given in, for example, Mt C is then summarized as:

$$\Delta C_l(i) = C_l(i+1) - C_l(i) \qquad (2)$$

and represents the net effect of inflow and outflow of the HWP pool of the HWP commodity class and thus the effects on the carbon balance, influencing the climate effects (Rüter et al. 2019).

Table 2 Default half-life times of the main semi-finished HWP commodity classes, based on Rüter et al. (2019)

HWP commodity class	Default half-life (years)
Sawnwood	35
Wood-based panels	25
Paper & paperboard	2

Globally, the annual HWP has increased by 10% to 210 Mt C yr^{-1} over the last 30 years, implying more wood harvest from forests during that time – estimated to represent 6% of the global carbon sink (Pan et al. 2024). Another estimate for the net annual sink of HWPs for 2015 was 335 Mt CO_2 eq $year^{-1}$ (Johnston and Radeloff 2019). These estimates represent 0.91 and 1.5 times the amount of the net EU LULUCF sink of 2021 (EEA 2023a). However, both estimates are based on regional or country-specific variability in, for example, the portfolio and share of HWP commodities produced, where type of forest management and setup of the wood processing industry are determining factors.

In the EU, the HWP carbon sink is estimated to be around 40 Mt CO_2 eq $year^{-1}$ (EC 2021a) and is urged – as a component of the LULUCF-reporting - to increase to an additional net sink of 50 Mt CO_2 eq $year^{-1}$ by 2030. For Sweden, despite being globally the 4th largest wood product exporter of pulp, paper, and sawnwood (Swedish Forest Industries 2023b), this poses a considerable challenge. This is because about 60% of the primary products' volume from domestic felling in Sweden is produced for applications with short half-life times, whereas at the EU level, the average is 34% (Cazzaniga et al. 2022).

Options to extend the HWP sink are either increasing the inflow of biogenic carbon into the pool or decreasing the outflow. To enhance the inflow, increasing harvest volumes is the most obvious option. In countries such as Sweden, however, where the current margin between annual felling plus natural mortality and forest increment has been shrinking for almost a decade, only a small space remains to further increase harvest rates (SCB and SLU 2023) which may risk future drain (incl. natural mortality) exceeding the increments. To decrease the outflow of carbon, two measures can be put forward. The first is extending the relative proportion of long-lived wood products of all wood products produced – for which great potential remains in the case of Sweden. Examples of this include the shifting of more wood for use in construction (Churkina et al. 2020; Schellnhuber 2024), e.g., in the form of cross-laminated timber (CLT). This implies that the share of wood products with a greater half-life time increases so that the outflow of biogenic carbon from the HWP pool decreases. The second measure is cascading wood use (EC 2016), which also aims to reduce the carbon outflow from the HWP pool. The idea of cascading is based on the principle that "wood is processed into a product and this product is used at least once more either for material or energy purposes" (Vis et al. 2016). Thus, cascading bears the potential to extend the retention of biogenic carbon in the HWP pool. This improved efficiency of resource use was found to improve the overall environmental performance of a wood use system (Höglmeier et al. 2015), including benefits for the climate (Thonemann and Schumann 2018). A general shift in HWP commodities, an increased application of cascading principles, and technological product developments (e.g., in terms of oriented-strand board made from pulpwood or residues) can thus provide potential to further the HWP C sink.

3.2.3 Forest value chain

Fossil emissions along the forest value chain are commonly assessed through the application of life cycle assessment (LCA), which is explained in more detail in Section 3.3. An example forest value chain could start with tree breeding, and range over planting and thinning operations to final felling, sawmill processing, product use, and final energy recovery. Across all these processes, fossil emissions in the form of CO_2, CH_4, and N_2O can arise. In general, the present as well as possible future fossil value chain emissions can be analyzed. This can be approached from different perspectives, while methodological decisions and parameter assumptions have a strong influence on the outcome. Results should be interpreted with this in mind.

At the EU level, a Member State's value chain emissions in the forest-based sector are part of official emission reporting to the UNFCCC. However, fossil GHG emissions associated with the manufacture of wood products or consumer goods from the manufacturing industry are usually reported in the source groups 'energy' and 'industrial processes' and are not allocated to individual economic sectors, such as the forest-based sector. Life cycle assessments that allocate recorded fossil value chain emissions to individual (wood) products therefore play no role in official reporting (Rüter 2023) but are relevant to better understand the product-specific environmental burden.

A central target of official emission reporting to the UNFCCC is to keep track of declared decarbonization efforts or commitments by the respective Member States to meet the targets of the Paris agreement. For Sweden, decarbonization efforts are prioritized since the country aims to be one of the world's first fossil-free welfare states with no net GHG emissions by 2045 (Ministry of Infrastructure of Sweden 2020). There are already large parts of Swedish industry which are based on fossil free energy supply. In the case of the Swedish forest-based sector, the supply of heat energy mainly originates from internal bioenergy generation and use (Swedish Forest Industries 2023a) and is thus characterized by substantially reduced fossil GHG emissions compared to the use of fossil energy carriers. Still, with its major industrial role, the forest-based sector - like all other industrial sectors in Sweden - is further urged to rapidly decrease GHG emissions (no matter whether it is biogenic or fossil) and increase removals, in order to meet the legally binding national climate neutrality target set for 2045 (Government Offices of Sweden, Ministry for the Environment 2020).

3.2.4 Substitution

The difference in fossil GHG emissions from a replaced alternative material or energy system by a functionally equivalent (wood) product system is called the substitution effect (Schlamadinger and Marland 1996; Sathre and O'Connor 2010; Leskinen et al. 2018). The substitution effect is a non-physical concept in contrast to the former components of a forest-based system – forest, wood products, and forest value chain. Therefore, it only appears indirectly in other sectors as reduced emissions in official GHG reporting to the UNFCCC (EC 2021a). This means that a net decrease in fossil GHG emissions happens only indirectly through the difference of increased forest industry-related emissions and reduced emissions from the alternative industry, given, for example an increase in wood use for a certain function, such as window frames. In this context, substitution effects occur only if wood use verifiably reduces the consumption of alternative materials formerly used for that function (e.g., aluminum window frames). This means that the emission reductions from the use of the wood product would not have occurred in the absence of the activity that generates the wood product (Arens et al. 2018). Substitution effects can thus only be accounted for implicitly where they are described in a prospective way (‘what if’), which makes the definition of a reference situation mandatory (Rüter 2023). A common way to assess the substitution effect is by means of substitution, or displacement factors (DFs). In the case of a single wood use (product scale), the DF can be described by:

$$DF_p = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \tag{3}$$

where the displacement factor of a single product (DF_p) is the difference in fossil GHG emissions of the avoided non-wood product ($GHG_{non-wood}$) and the fossil GHG emissions of the wood product (GHG_{wood}), divided by the difference in the amounts of wood used in the wood product (WU_{wood}) and the non-wood product ($WU_{non-wood}$), given in Mg $\mathrm{C_{fossil}}$ $\mathrm{Mg^{-1}}$ $\mathrm{C_{biogenic}}$ (Sathre and O’Connor 2010). The greater the difference in the fossil GHG balance (numerator of the formula) and/or the smaller the wood use intensity (denominator of the formula), the higher the DF and thus the quantity of avoided fossil emissions, expressed in fossil carbon, per unit of biogenic carbon. In the past, numerous studies have been performed to ascertain the $\mathrm{DF_p}$ of wood uses for effective fossil GHG avoidance on a product level (Leskinen et al. 2018; Myllyviita et al. 2021). However, even if a DF on the product scale may be high, it does not necessarily mean that substitution on a regional or national level is high. Therefore, one must also account for the various wood uses at the regional or national level which fulfil many different functions (market scale). Accordingly, the above formula requires extension:

$$\begin{aligned} DF_m(t) &= \sum \frac{DF_{pi}(t) \times W_{pi}(t)}{W_{pi}(t)} \\ &= \frac{DF_{p1}(t) \times W_{p1}(t) + DF_{p2}(t) \times W_{p2}(t) + \cdots + DF_{pn}(t) \times W_{pn}(t)}{W_{p1}(t) + W_{p2}(t) + \cdots + W_{pn}(t)} \end{aligned} \tag{4}$$

where the weighted average displacement factor for a market (DF_m) given for a number of HWP end uses (n) in a certain year (t) equals the sum of all product displacement factors (DF_{pi}) multiplied by each weight, i.e., the amount of each HWP end use considered (i), divided by the weight, expressed, as with the previous formula, in Mg C_{fossil} Mg^{-1} $C_{biogenic}$ (Hurmekoski et al. 2021).

In several cases, DFs were applied to relate the effects of wood use to forest management and thus create a "complete" balance of the management effects (Rock and Rüter 2023), examples for Sweden being Skytt et al. (2021) and Petersson et al. (2022). However, methodological requirements of standardized LCAs are often omitted (e.g., definitions of functional units), or it is assumed that the fossil GHG emission difference determined for a certain semi-finished wood product is generally transferable across all end-uses of that semi-finished wood product (Rock and Rüter 2023). An overriding premise in assessing the substitution effect by means of displacement factors is that increasing production of the wood-based commodity in question results in an equal increase in total consumption thereof. Accordingly, the substitution effect increases merely as a consequence of increasing wood production. For example, if in a climate impact assessment, a scenario of increased harvest which compares to a baseline harvest scenario is modelled, the entirety of the additional quantity of wood commodities of the increased harvest scenario may be assumed to yield a larger substitution effect, compared to the baseline harvest scenario. This, however, amounts to an implicit assumption of perfectly elastic demand (Mas-Colell et al. 1995) which is rarely the case. A general shortcoming associated with climate impact assessments applying displacement factors is, therefore, that substitution effects risk being overestimated and misjudged (Leturcq 2020; Harmon 2019). In this context, decarbonization efforts, in the forest-based sector and beyond, further contribute to an uncertainty about future substitution effects, which may decrease or increase (Brunet-Navarro et al. 2021). One method of reducing misjudgment about some critical assumptions is to consider econometric analysis in the substitution effect assessment. This accounts for the own price- and cross-price elasticity of the wood products, i.e., the change in consumption following a unit change in the own price, or the price of an alternative product (Mas-Colell et al. 1995).

3.2.5 System perspective

The simultaneous consideration of the aforementioned components (forest, wood products, value chain and substitution) in climate impact assessments is recognized to be a system perspective (EC 2021a; Cowie et al. 2021). In the understanding of this thesis, the system perspective entails the assessment scope and the assessment approach. The assessment scope defines *what* is taken into account when estimating the contribution of forest-based systems to climate change mitigation, comparable to the system boundary concept used in LCA. The assessment approach defines *how* the GHG balances of forest-based systems are estimated in the climate impact assessment.

The assessment scope from a system perspective (i.e., the *what*) can be applied in two contrasting ways. On the one hand, the scope can focus on a single wood use representing a single function / functional unit (e.g., ‘living area’) (see Section 3.3.1), which is comparable, but not restricted, to product LCAs, with examples such as Hammar et al. (2015), Røyne et al. (2016), Peñaloza et al. (2019), D’Amico et al. (2021), Andersen et al. (2021), or Schulte et al. (2021). For this assessment scope, the term ‘product scale’ is used in this thesis. On the other hand, it can concern multiple wood uses, for which the term ‘market scale’ is used in this thesis. Here, multiple functions / functional units (e.g., ‘living area’, ‘EU norm pallet’, ‘energy content’) are analyzed, which is typical, but not restricted to regional or national level assessments, with examples such as Hurmekoski et al. (2020), Skytt et al. (2021), or Petersson et al. (2022).

Next to the assessment scope, the assessment approach (i.e., the *how*) can also be done in two ways as understood in this thesis. This means that the assessment approach can be driven by either the supply or the demand of additional harvest volumes or HWPs. Therefore, each assessment approach can be applied to either assessment scope, either on the product scale or market scale (with hybrid forms also existing) (see Figure 1).

An illustration of the modelling of the different assessment approaches is given in Figure 3. In the supply-driven approach, the quantity of the HWP(s) fulfilling one or multiple functional units is steered by activity within the forest (‘*forest to function*’, Paper I & II). Assessments from ‘*forest to function*’ include a refence forest management against which alternative forest management scenarios are compared, leading to, for example, a change in harvest supplies. At first, forest carbon balances as a consequence of changes in forest management are assessed, as are the implications for the technosphere, ultimately leading to a changed supply in wood for the functional units. Versions of this climate impact assessment approach for forest-based systems have been applied, for instance, for the United States (Dugan et al. 2018), France (Valade et al. 2018), Canada (Moreau et al. 2022), Japan (Matsumoto et al. 2016), Mexico (Olguin et al. 2018), and Sweden (Lundmark et al. 2014; Gustavsson et al. 2017; Gustavsson et al. 2021; Skytt et al. 2021; Petersson et al. 2022; Schulte et al. 2022).

Under the demand-driven approach, the modelling sequence is flipped compared to the supply-driven approach and ranges from '*function to forest*' (Paper III). First, the product scale LCA results of a certain wood use fulfilling a functional unit and its counterpart are assessed, potentially including required material inventories. An example for this is the fulfillment of the function 'living area' by either a timber frame house or concrete frame house, for which a variety of materials are required. After the product scale LCA results are collected, each alternative, a timber frame house or concrete frame house, which matches fulfillment of the functional unit is scaled up to, for example, a regional or national level based on the respective statistical or official demand data to form a reference scenario. Next, alternative 'what if' scenarios are defined. The respective difference between the reference and the alternative scenarios is the GHG mitigation potential which originates from the changed relative share between the wood and non-wood alternative as a percentage of the total officially projected demand to fulfill the functional unit / function in question. Another example of a demand-driven climate impact assessment ascertaining increased wood use could be given in terms of, for example, the functional unit 'window frame'. Here the modelling sequence within a system perspective would start with the required additional quantity of the wood commodity in question: 'How many window frames (regardless of type) are required for the case and time horizon under study?' Subsequently, the implications for the technosphere are assessed with the knowledge of the relative shares between wood window frames and alternative materials. After definition of a reference scenario and an alternative 'wood' scenario, the following questions would arise: 'How much fossil GHG emissions are avoided?', 'How large are the additional fossil value chain emissions?' and 'How much additional HWP carbon storage is given between the reference and alternative scenario?' After that, changes in forest carbon are analyzed, posing questions like 'If all window frame construction under the considered time horizon and area under study used wood as the raw material, what would be the change in the forest carbon sink, for example, as a consequence of increased harvests in the same area?'. In this way, the demand-driven approach follows the modelling sequence from '*function to forest*'. This approach remains rather unexplored in climate impact assessments of forest-based systems since it is very data intensive. Two examples assessed the national implications in terms of climate impacts from increased wood construction in Germany (Hafner and Rüter 2018), and Sweden (Schulte et al. 2023).

In the hybrid assessment approach '*fiber to forest or function*' the change in HWP supply originates from within the forest value or supply chain. For example, this may be a change in the recycling rate of a certain HWP. Although labelled hybrid at this point, the approach is mainly characterized by a similar modelling logic as the supply-driven approach, since no actual statistical data about the demand of a certain wood product is considered. Versions of this approach were conducted for Switzerland (Suter et al. 2017) and Finland (Hurmekoski et al. 2020) to test the climate impact of cascading or a more preferable wood use ratio, as well as for increased paper recycling in Sweden (Schulte et al. 2024).

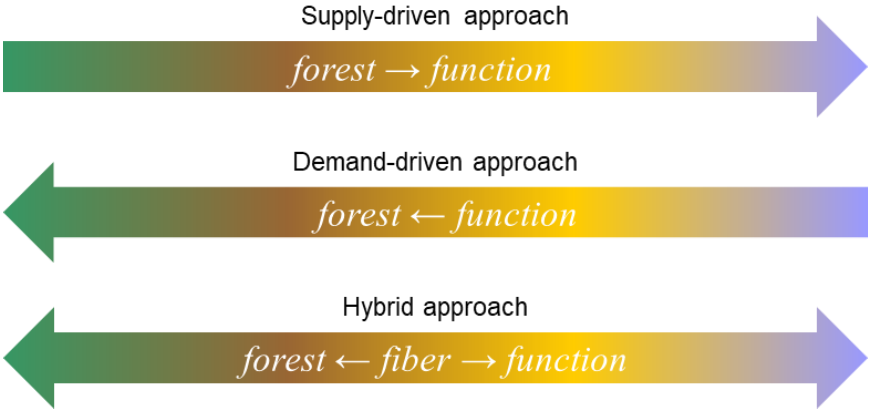

Figure 3 The modelling sequence in climate effects assessments of forest-based systems following either a supply-driven ('*forest to function*'), demand-driven ('*function to forest*'), or hybrid approach ('*fiber to forest or function*'). The sequence of colors green, brown, yellow, and purple represent the modelling order of a system perspective and its four components: forest, wood products, forest value chain, and substitution, (see Figure 1 and Figure 2).

3.3 Life cycle assessment

3.3.1 Life cycle assessment methodology

Life cycle assessment (LCA) is a standardized methodology to investigate the environmental impact of products and services along all stages of their life cycle (ISO 2006a, 2006b). These stages typically include sourcing, extraction or cultivation of materials (cradle), processing of the materials to products, use of the products, and the ‘end-of-life’ of the products (grave), while transport is included between the stages.

An LCA is divided into four phases which are conducted in an iterative manner (ILCD 2010). The first phase, ‘goal and scope definition’, sets the foundations for the study. The aim of the assessment and the system boundaries – representing the spatial and temporal delimitations - are defined, as is the target audience. The second phase, ‘inventory analysis’, deals with the collection of required life cycle inventory (LCI) data, which are necessary to model the system under study. LCI data include information about the required input and output flows of physical materials and energy, as well as the emissions of a process. The third phase, ‘impact assessment’, quantifies the environmental impact of the system under study based on the LCI data. This can be done by either focusing on a single environmental impact category, such as global warming, or on multiple categories, for example, eutrophication and acidification. The last phase of an LCA is ‘interpretation’, which connects to all other phases and aims to critically reflect on the assumptions made or results obtained.

One crucial assumption of every LCA concerns the functional unit which must be defined in the ‘goal and scope definition’ phase (ILCD 2010). The functional unit is the pivotal point of an LCA and defines what is being studied, quantifies the product or service delivered by the studied system, and provides a reference to which all inputs and outputs of the system relate. In addition, the functional unit forms a basis for comparing alternative products or services, for example, with regard to an environmental impact category. Within an LCA which considers, for example, a paperboard production system, the environmental impact could be matched for the functional unit of “the input of 1 m^3 pulpwood” or the output of “1 Mt paperboard”.

Two general types of LCA exist: ‘attributional’ and ‘consequential’ (Ekvall 2020); These affect the choice of the system boundaries, functional unit, etc. The distinction between the two is in how the environmental burden is interpreted. Attributional LCA estimates the extent to which the global environmental burden can be *attributed* to the system under study, for which average data is used. Consequential LCA estimates how the global environmental impact is affected as *consequential* to the system under study for which, ideally, marginal data is used. Theoretically, a clear distinction between the two approaches is recommended, yet, in practice, many LCAs include characteristics of both types (e.g., due to missing marginal data).

3.3.2 Life cycle assessment of forest-based systems

The first LCAs of the European forest-based sector date back to the 1990s, yet comparability among results from scientific studies is still difficult due to numerous options for the main methodological choices which must be made (Klein et al. 2015; Cowie et al. 2021). Among these are setting an appropriate land use baseline, or definition of the spatial and temporal system boundaries.

The land use baseline is of great importance because it is required to distinguish the environmentally relevant anthropogenic flows in the forest-based system under study from those that occur in the absence of that system (Soimakallio et al. 2015; Peñaloza et al. 2019). A land use baseline is mandatory in the assessment and is often only implicitly given, without clear definition. For example, in the assessment of a production forest, either continuation of the current business-as-usual forest management or natural forest regeneration could be considered as alternative land use baselines. If one or the other baseline is assessed compared to a scenario of increased harvest, the outcome of the analysis (e.g., the carbon balances) would differ. These changes in the carbon balance can be understood as direct land use change (dLUC). Alongside dLUC, there is also indirect land use change (iLUC), which occurs when, for example, a change in forest management in one region induces a change in land use in another region with respect to harvest volumes, or biogenic carbon alterations. This process is referred to as leakage and can risk compromising climate change mitigation achievements in one region due to additional harvests or emissions in other regions (Chomitz 2002; Nepal et al. 2013). For Sweden, market effects leakage, in the form of the rate at which nationally decreased harvests are compensated elsewhere, was found to range between 59-81% (Hu et al. 2024). For sawn timber, pulpwood, and firewood, leakage in Sweden is considered to range between 24-27%, 44-53% and 26-72%, respectively (Lundmark 2022).

Spatial system boundaries for forests can be considered from a ‘stand’ level, or from a ‘landscape’ level (Lamers and Junginger 2013; Cowie et al. 2021). A stand-level solely assesses the developments of, for instance, one forest plot, stand or hectare, which, in a Nordic forest setting, due to dominant clear-cut forest management, implies an equal age class distribution under the site-specific conditions of forest growth. This spatial perspective is suitable for a product scale assessment and is advantageous when studying site-specific characteristics, however, can be misleading, for example, for initial carbon stocks. The landscape-level includes the growth, age, and species-related dynamics of a whole landscape. Different landscape definitions also exist, such as ‘theoretical’ landscapes and ‘real’ landscapes (Cintas et al. 2016). A theoretical landscape consists of identical stands of different ages, i.e., it is a time-shifted stand-level (Eliasson et al. 2013). A ‘real’ landscape-level relies on regional forest data and is based on, for example, a National Forest Inventory (NFI).

Temporal considerations are of crucial relevance in forest-based systems. Whereas formerly sustainable biomass growth and harvest were often considered to be ‘carbon neutral’ in traditional (static) LCA (Pawelzik et al. 2013), time-dependent (or time-dynamic) accounting is recommended practice today (Levasseur et al. 2010; Cowie et al. 2021). This is because the temporal difference between emission and sequestration of CO_2 results in a change in its atmospheric concentration, leading to changes in radiative forcing and atmospheric temperature (Helin et al. 2013). As a result, different results can emerge, for example, on a stand-level, depending on whether forest growth is considered to occur either prior to or after harvest (Peñaloza et al. 2019). Moreover, the conclusions of a study strongly depend on the length of the time frame or time horizon chosen for the assessment. For example, for Sweden, reduced forest use intensity was found to yield climate benefits in the short-term (< 50 years) (Skytt et al. 2021), yet, in the long-term (> 50 years), continuously active forest use was found to yield larger climate benefits (Petersson et al. 2022). The temporal definitions between short- and long-term can however vary.

3.3.3 Climate impact assessment methodology

Global warming, or climate change, is the most common environmental impact category analyzed in LCA. The most frequently applied metric among the atmospheric cause-effect chain, ranging from the emission of GHGs to atmospheric temperature change, is global warming potential (GWP), which is expressed in CO_2 equivalents (eq). The GWP is calculated by:

$$GWP\ (H) = \frac{CRF_x(H)}{CRF_{CO_2}(H)} \tag{5}$$

where the cumulative radiative forcing, i.e., the difference between incoming and outgoing radiation of a specific GHG (CRF_x), for a certain time horizon (H) is divided by the cumulative radiative forcing of CO_2 (CRF_{CO_2}). Typically, the time horizon considered is 100 years (GWP_{100}), but shorter time horizons, such as 20 years (GWP_{20}), can also be applied. Depending on the life lengths of the GHG, the choice of the time horizon can be very influential on the results, especially for systems prone to large emissions of short-lived CH_4. Since the GWP is the most frequently applied climate metric, it offers the advantage of providing a good basis for enhancing comparability between studies. However, results based on the GWP do not make the dynamics transparent which occur across the considered time horizon. For time-dynamic (forest-based) systems, climate impact metrics which account for time-dependent developments can offer advantages. Here, the absolute global temperature change potential (AGTP) is one alternative (IPCC 2021). The AGTP is described by:

$$AGTP_x = \int_0^H RF_x(t) \times R_T(H-t) \tag{6}$$

where temperature change (AGTP) expressed in Kelvin (K) per unit of a GHG (x), is formed by the radiative forcing (RF) of that GHG in a year (t) and multiplied by a climate response function (R_T) over the integral of the time horizon (H). The AGTP has been applied in various studies investigating the climate impacts of, for example, bioenergy systems (Porsö and Hansson 2014; Hammar 2017) as it proved to satisfactorily represent the underlying time dynamics of the systems (Ericsson et al. 2013).

3.4 Forest models

The use of forest models frequently forms the basis of climate impact assessments of forest-based systems. These models enable the creation of scenarios about the future development of biogenic carbon stocks in above and below ground biomass, litter, dead wood and soils, as well as harvest volumes. Examples for European forest models include the Carbon Budget Model (CBM-CFS3) (Kurz et al. 2009; Pilli et al. 2015), the European Forest Information Scenario Model (EFISCEN) and EFISCEN-Space (Schelhaas et al. 2007; Schelhaas et al. 2023), as well as the European Forest Dynamics Model (EFDM) (Packalen 2014) (Schelhaas et al. 2017). All of these forest models are intended to provide improved policy information concerning decision making about forestry and ecosystem service management, such as forest carbon sequestration.

In Sweden, the most frequently applied forest model is the forest decision support system Heureka (Wikström et al. 2011; Lämås et al. 2023), dedicated to multi-criteria forestry planning and forest analysis. The system is developed and hosted by the Swedish University of Agricultural Sciences. It contains four software packages: StandWise - for analysis of individual stands; RegWise and PlanWise – applicable on either the stand, landscape/regional, or national level, where RegWise is based on a rule-based simulation framework to run explorative simulations serving to study ‘what if’ questions, and PlanWise uses optimization techniques to study normative questions, such as how to achieve a desired harvest regime; and PlanEval – based on a multi-criteria decision analysis. Forest input data is either stand-level data, for example, from a stand register database, or sample plot data, such as from the NFI. The outputs, such as timber production, carbon sequestration, dead wood dynamics, habitat for species, recreation, or susceptibility to forest damages (spruce bark beetle, wind-throw and root rot) are given in five-year periods. The Heureka system is used for nation-wide forest impact analysis for policy support and by all large and medium size forest owners for their long-term forest planning. This means that Heureka influences forest management decisions on more than 50% of the Swedish forest area (Lämås et al. 2023).

For climate impact assessments of forest-based systems, forest growth and mortality are of key importance. Modelling of these in Heureka is based on certain growth and mortality functions. For above-stump tree biomass, these functions are based on models from Marklund (1988) and for stump and root biomass on Petersson and Ståhl (2006). In young forest stands, above-ground tree biomass is estimated using models from Claesson et al. (2001), and the decay of coarse woody debris is based on Kruys et al. (2002) and Sandström et al. (2007). The calculation of SOC developments in mineral soils relies on the Q-model (Ågren and Hyvönen 2003), which computes continuous soil organic matter decomposition and emission factors for peatland. Input to the Q-model is provided by a litter production model and by harvest residues. The carbon in deadwood is analyzed using exponential decay rates from dead wood inflow subsequent to tree mortality (Harmon et al. 2000).

4. Material & Methods

4.1 Overview & system boundaries

Each Paper, I-IV, analyzed the climate effects of a particular forest-based system. In all cases, this was done by integrating forest carbon dynamics with time-dynamic LCA-methodology and a climate impact assessment. To that end, each analysis included the time-dynamic (annual) modelling of the previously described components of a system perspective: biogenic carbon fluxes in (i) forests and (ii) wood products, as well as fossil GHG emissions from (iii) forest value chain and (iv) substitution effects, as illustrated in Figure 4. Balances of biogenic carbon and fossil GHGs were accounted for separately and brought together for the climate impact assessment in which the GWP and the AGTP were calculated, based on the methodology described under Section 3.3.3. In every Paper, the modelling of each component was adapted to its particular aim. As to the geographical set-up, Papers II-IV were solely based in Sweden, with Paper II focusing on three Swedish regions (south, central, north) and Papers III-IV on the entire country. Paper I differed in terms of the geographical scope as the modelled value chain was based in both Sweden and Uruguay. The time horizon considered in every Paper was a minimum of 50 years (2020-2070). In Paper II, the time horizon was extended to 200 years to study the effects of multiple forest rotations on the climate impact.

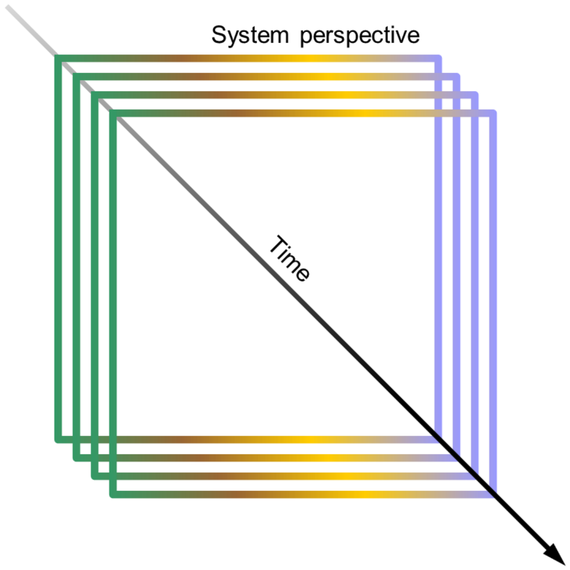

Figure 4 Conceptual illustration of the time-dynamic application of a system perspective in Papers I-IV, including the implications for forests (green), HWPs (brown), the forest value chain (yellow), and the substitution effects (purple). Every new version of the frame, representing the system perspective, represents another year of accounting. Compare Figure 1 and Figure 2.

4.2 Forest carbon modelling

The modelling of the ecosphere, or forest system, constituted the basis for the assessment of Paper I and II, while in Paper III and IV, it was a consequence of previous modelling steps. In the first two papers, the modelling encompassed the assessment of biogenic carbon fluxes within the forest system, defining the amount and type of supplied harvest volumes. In the latter two papers, the forest modelling solely identified the forest carbon fluxes.

4.2.1 Eucalyptus plantation

In Paper I, the forest system was in Montes del Plata, Uruguay; this allowed for the study of the biogenic carbon dynamics of Eucalyptus being used as feedstock for South American pulp delivered to Sweden for further processing. The biomass modelling of the plantation was based on primary data at the stand-level. Stems were harvested and the remaining biomass, in the form of, for example, leaves, was assumed to be left on the plantation to convert to SOC, modelling for which was done using the dynamic soil carbon model Yasso 15 (Järvenpää et al. 2018). Grassland was assumed as the land use baseline and a theoretical landscape was modelled to study the biomass growth from a time-dynamic manner with annual harvests (Cintas et al. 2016). The annual harvest was based on collected stand-level data. The rotation period of each Eucalyptus plantation was 9 years, and an average harvest yield amounted to 77 Mg pulpwood ha^{-1}, with a biogenic carbon content of 38.5 Mg ha^{-1}. The biogenic carbon fluxes (i.e., stock-changes) were converted into CO_2 based on the molecular mass ratio of CO_2 (44) and C (12) and were subsequently used for the climate impact assessment. The harvest volumes were converted to mass and used for further calculation of the HWP carbon storage as well as fossil GHG balances.

4.2.2 Forest modelling

In Papers II-IV, the forest system was based in Sweden and modelled via the forest decision support software Heureka (Lämås et al. 2023). In Paper II, Heureka RegWise was used to simulate implications for the question ‘What climate effects arise if Swedish rotation forest management is changed?’. To this end, the Swedish regions of Kronoberg (southern Sweden), Värmland (central Sweden), and Norrbotten (northern Sweden) were analyzed, focusing on four forest management scenarios relative to a reference forest management representing current practices as based on NFI data from 2014-2018. The four forest management scenarios included an increase or decrease of 20% of either the minimum relative final felling age (affecting the average rotation length), or the harvest intensity as a percentage of the growth. Results for each scenario were compared to the reference forest management, which was characterized by a harvest level of 83% of the growth rate on productive forest land, as based on the Swedish FRL with reference period

2000-2009 (SME 2019), and rotation lengths based on the minimum relative final felling age as defined by the Swedish Forestry Act (see Table 3 for details).

Table 3 Selected forest data for all Swedish regions included in Paper II

Property	Unit	Norrbotten (north)	Värmland (central)	Kronoberg (south)	Reference
Productive forest area	Mha	3.93	1.35	0.67	NFI 2014-2018
Average final felling age	Years	116	108	99	NFI 2014-2018
Average minimum final felling age	Years	85	64	58	NFI 2014-2018
Harvest level	% of growth	83	83	83	(SME 2019)

The output variables of Heureka RegWise were biogenic carbon in standing biomass, dead wood, and SOC, as well as harvest volumes from sawlogs, pulpwood, fuelwood, and residues. The division of the harvest volumes is predefined in Heureka based on the stem diameter, where >13 cm are sawlogs, 13-5 cm are pulpwood, and the rest are fuelwood or logging residues. The five-year period outputs from Heureka RegWise were interpolated to annual values and converted to CO_2, for the climate impact assessment of the forest carbon fluxes, or into C, to calculate HWP carbon storage or fossil GHG emission profiles and substitution effects, similar to Paper I.

The Swedish forest modelling in Paper III and IV was done on a national level and used Heureka PlanWise to investigate the forest carbon changes following the fulfilment of a certain harvesting objective. This meant that a reference forest management including a baseline harvest volume was defined, against which another forest management scenario including a 'target' harvest volume was compared. Thus, the 'target' harvest volume was the input variable, which affected the output variable, i.e., the change in forest carbon stocks. In both Paper III and IV, the forest reference was based on the 'business-as-usual' scenario of the official Swedish forest impact analysis “Skogliga konsekvensanalys 2022” (SKA 22) (Eriksson et al. 2022) and included only productive forest land in Sweden (where growth >1m^3), based on NFI data from 2020.

The reference sawlog harvest in Paper III and the reference recycled paper supply in Paper IV were based on projections from the Global Biosphere Management Model (GLOBIOM) (Havlík et al. 2018; Lauri et al. 2021). In Paper III, the ‘target’ harvest volume was set by the demand-driven additional annual sawlog harvest, which was required to fulfill a full concrete-frame substitution with timber-frame in Swedish multi-family housing construction (MFHC). In Paper IV, the ‘target’ harvest volume was set by the additional recovered pulp, which was available due to the assumed increased paper recycling rate. One investigated strategy in the assessment consisted of saving the pulpwood harvest volume from replacement of primary pulp with recovered pulp in papermaking. The ‘target’ harvest volumes, i.e., additional sawlogs (Paper III) and saved pulplogs (Paper IV), thus defined the change in forest carbon stocks as induced by the comparison to the forest carbon reference. The five-year period outcomes were, like in Paper II, interpolated into annual values and converted into CO_2 for the climate impact assessment.

4.3 HWP carbon modelling

The HWP carbon storage was based on the IPCC *Good Practice Guidance* (Rüter et al. 2019) as described under Section 3.2.2. It was aspired to account for biogenic carbon storage in the products, not solely at the semi-finished product level but at the finished product level, if data was available. Wood flow modelling was conducted accordingly. The HWP carbon storage was always accounted for in a relative sense, i.e. an implicit baseline was included. This was either no production of the wood-based product (Paper I), continuation of the reference forest management (Paper II), continued dominance of concrete frame in MFHC (Paper III), or a baseline paper recycling rate (Paper IV).

For Paper I, the carbon storage accounting concerned Eucalyptus pulp and its subsequent production into liquid packaging board used for beverage cartons. For this, a half-life time of 2 years was applied. At the end-of-life, energy recovery was assumed, so one cascading step of the biomass utilization was considered.

In Paper II, the wood flow modelling and HWP carbon assessment ranged over an entire portfolio of wood products, as shown in Figure 5, for which fossil value chain emissions (Section 4.4) and substitution effects (Section 4.5) were also assessed. The applied half-life time for sawnwood-based products was 35 years; for panel & boards, it was 25 years; and for paper & paperboard, it was 2 years (as shown in Section 3.2.2). In addition, a 5-year half-life time was assumed for viscose. Wood used for energy had a 1-year half-life time. Carbon storage was considered for about 95% of the harvest volume, while for the remaining 5%, the end use was unknown, as was information about any possible carbon retention.

In Paper III, the demand for MFHC and the scenario of a total substitution of concrete frame by timber frame steered the HWP carbon storage. Since the assessment was demand-driven, the total additional HWP biogenic carbon storage originating from the shift to timber-frame construction was constrained by the projections of the Swedish Housing, Building and Planning Agency (Boverket) (Boverket 2021) and by demographical data from Swedish statistics (SCB) (SCB 2022). Similarly to Paper II, the half-life times for the semi-finished wood product level were applied to the wood end uses. The end uses of wood were based on material inventories for the timber and concrete frame dwelling types, where the timber frame alternatives distinguished between a timber-light frame and a cross-laminated timber frame (Gustavsson et al. 2017).

In the wood flow modelling of Paper IV, HWP carbon storage was considered in the scenario where the additionally recovered pulp originating from an increased paper recycling rate was used to produce additional MMCF to substitute for cotton fiber (Figure 6). Here, a half-life time of 5 years was applied for the MMCF (similar to Paper II) and 35 years for the by-product lignin, which was used as a concrete admixture (Domsjö Fabriker 2022).

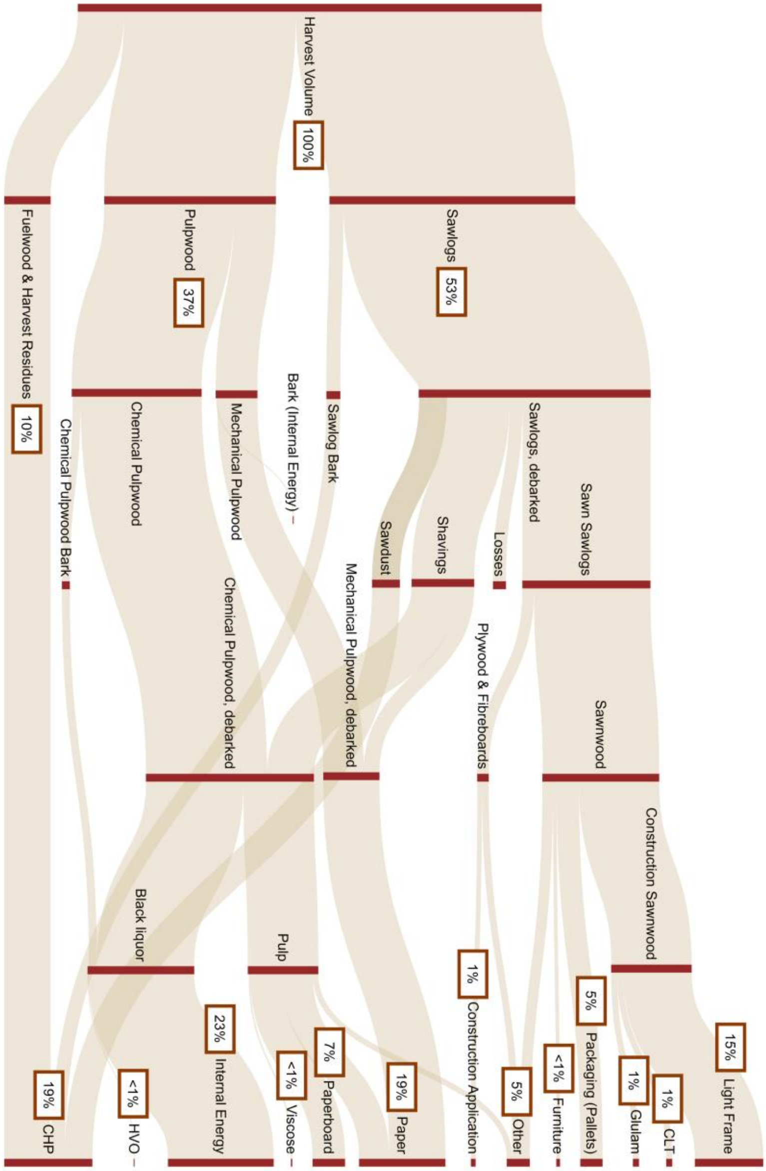

Figure 5 Sankey diagram of wood flow modelling in Paper II. HWP carbon storage, as well as value chain emissions and substitution, were accounted for based on the quantity at the finished wood product (end use) level. For the HWP carbon storage, the half-life times of the underlying semi-finished wood product categories were applied. Note: CLT = cross-laminated timber, HVO = hydrogenated vegetable oil, CHP = combined heat and power.

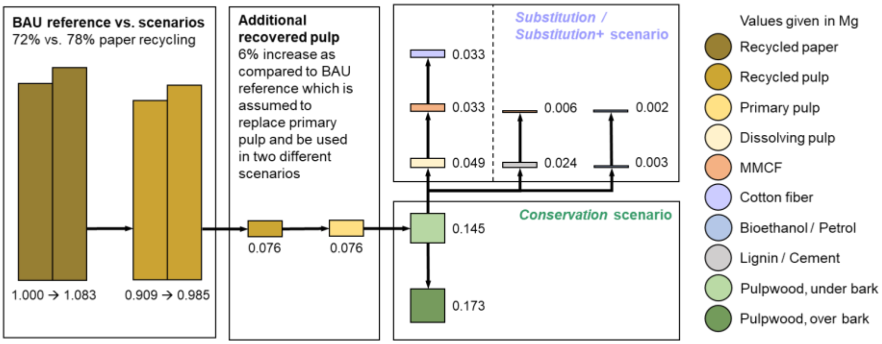

Figure 6 Modelling framework of Paper IV, including the wood flow modelling and conversion steps which were used to calculate the quantity of saved pulpwood in the *Conservation* scenario, and HWP carbon storage in the *Substitution* / *Substitution+* scenario. Note: MMCF = man-made cellulosic fiber

4.4 Value chain emissions

In Papers I-IV, fossil GHG emissions along the forest value chain were accounted for annually using a time-dynamic approach. In Paper I and II, they were based on the yearly harvest output from the forest system and in Paper III and IV, were based on the annual MFHC demand or increased recovered pulp supply, respectively. In all Papers other than Paper III, the fossil GHG emissions were accounted for from ‘cradle-to-grave’. For Paper III, the fossil emissions of a use-phase and end-of-life phase were excluded. This was, firstly, because accounting for a use-phase was negligible since the compared flat alternatives were functionally equivalent during their time of usage (Gustavsson et al. 2017) and, secondly, because the buildings’ lifetime exceeded the considered time horizon of 50 years, so the newly constructed timber frame-based flats would not reach their end-of-life. In all Papers, the majority of the used emission information relied on LCI data from the ecoinvent database (Wernet et al. 2016), which was added as supplementary material to each published study. Detailed information as to which product or process led to which amount of fossil GHG emissions can be found there. The value chain emissions in all assessments were kept constant over the respective time horizons due to insufficient knowledge about their future development, e.g. concerning decarbonization. Only in Paper I was a sensitivity analysis conducted to test the energy substitution effect with regards to different marginal electricity mixes in the form of a shift from fossil-based energy towards more renewable energy.

4.5 Substitution effects

4.5.1 Supply-driven substitution effects

In Papers I, II and IV, the substitution effects were based on the supply of either wood harvest (Paper I and II) or additional recovered pulp (Paper IV), which was assumed to be a perfect substitute for pulpwood. In all cases, the substitution effects were calculated in a relative sense, i.e., compared to a reference situation, as explained in Section 3.2.4 and Section 4.3.

In Paper I, Eucalyptus pulpwood was the feedstock for the production of pulp, liquid packaging board and, finally, the beverage carton. Due to its supply, the beverage carton was assumed to replace a functionally equivalent polyethylene terephthalate (PET) bottle (material substitution) and marginal energy sources (energy substitution) from waste incineration in Sweden and from the by-product combustion in Uruguay. As mentioned above, a sensitivity analysis changed the marginal energy sources towards more shares of renewable energy, and next to this, the replacement ratio between the beverage carton and the PET bottle.

In Paper II, Heureka RegWise defined the harvest volume assortments of sawlogs, pulpwood, fuelwood and residues, as described under Section 4.2.2. Subsequently, the assortments were broken down into the semi-finished and the finished wood product levels (Figure 5) (SFA 2014; CEPI 2020; Hurmekoski et al. 2020; Rudenstam 2021; SFI 2021). On the finished wood product level, functionally equivalent non-wood products were determined, and product displacement factors were calculated, based on the fossil GHG emission profiles of the respective materials and the methodology as described under Section 3.2.4. In addition to this, a ‘replacement rate’ accounted for each finished HWP, since meeting the same function among wood and non-wood materials can require different mass quantities of each. The majority of LCI data was based on the ecoinvent database (Wernet et al. 2016). A summary of the materials and displacement factors for Paper II is shown in Table 4. In a sensitivity analysis, the replacement ratio of all materials was increased or decreased, which had an influence on the overall substitution effect.

Table 4 Summary of assumptions and variables for assessing the substitution effect in Paper II from a supply-driven approach by displacement factors (DF). Note: further short forms, e.g., HVO, are explained under Section Abbreviations.

Semi-finished HWP	End-Use / Finished HWP	Substituted Material / Product	Functional Unit	Replacement Ratio	DF (Mg C Mg C^{-1})
Sawnwood	Construction	Concrete Steel	Application in Multistory Residential Building	9.7 0.2	0.8
	Packaging (Pallets)	HDPE	EU Norm Pallett	0.2	0.4
	Furniture	Steel, PP, PUR, glass, aluminum, PVC	Average Furniture Article	0.1	0.0
	Other	-		-	-
Plywood + Fiberboard	Construction	Gypsum, Mineral Wool, Plaster	Application in Multistory Residential Building	0.2	-0.6
	Other	-		-	-
Pulp & Paper	Paper	-		-	-
	Paperboard	PET	Average Paperboard Packaging	0.5	1.1
	Viscose	Cotton, Polyester	Mass Based	1	0.4
	Other	-		-	-
CHP	Heat & Electricity	Natural Gas	Energy Content Based	1	0.4
Biofuel	HVO	Diesel		1	1.4
Weighted Average (DF_m)					0.6

The substitution effect in Paper IV was generally assessed from a supply-driven perspective, with the exception that the additional feedstock did not originate from the forest (‘*forest to function*’). Instead, it was derived from the increased paper recycling rate leading to an additional recovered pulp supply (‘*fiber to forest or function*’). In one scenario of Paper IV, this additional recovered pulp was assumed to replace primary pulp in papermaking. The exempt primary pulp was used for the production of dissolving pulp and MMCF, the supply of which was assumed to substitute for cotton fiber. The by-products from producing dissolving pulp, hemicellulose and lignin, were either assumed to be used for pulp mill-internal energy recovery, or further processed into ethanol (from hemicellulose) and a concrete admixture (from lignin). Again, the substitution effect was assessed as the relative difference in avoided fossil GHG emissions compared to the reference scenario. This reference maintained paper recycling at current rates so that no additional recovered pulp supply was given. In a first sensitivity analysis, the impact on the climate effects was tested as regards the ‘pp-ratio’. The pp-ratio was the ‘primary pulp to pulpwood’ ratio and represented the amount of pulpwood savings as equivalent to the quantity of saved primary pulp (compare Figure 6). A higher pp-ratio thus meant that a larger pulplog quantity could be used for dissolving pulp and MMCF making in the *Substitution* / *Substitution+* scenario. On the other hand, changing the pp-ratio influenced how much pulpwood could be saved under the *Conservation* scenario. In a second sensitivity analysis, the replacement ratio between MMCF and cotton fiber was changed to account for partial complementarity and a more efficient substitution between the two materials. Paper IV is, therefore, not categorized to be entirely supply-driven, but is a hybrid (Figure 1), as it includes aspects considering the demand of the wood products under assessment (partial complementarity in sensitivity analysis, departure from reduced demand for primary pulp).

4.5.2 Demand-driven substitution effects

In Paper III the substitution effects departed from the projected demand for a specific wood use (MFHC), which, up to now, is mainly based on concrete frame in Sweden (Figure 7). As mentioned under Section 4.3, the demand numbers until 2030 were based on projections from the Swedish Housing, Building and Planning Agency, Boverket, and extended to 2070, relying on demographical data from Swedish statistics, SCB. They amounted to approximately 55,000 additional dwellings per year. The general scenario of Paper III consisted of a hypothetical total replacement of the concrete frame dominance with timber frame by 2030, maintaining the rate of 100% timber frame-based construction until 2070. The maximum achievable substitution was thus constrained by the total of required additional multi-family housing units (dwellings), as described above. This constraint acted as a safeguard against unfeasible, or unrealistically high, cases of substitution. The substitution effect was the difference in fossil GHG emissions between the reference scenario representing the continuation of concrete-frame dominance, and the scenario in which timber-frame replaces all concrete frame by 2030 and continue to do so until 2070. The calculation of displacement factors was a possible feature. Two alternative scenarios of wood frame were modelled for the national scale MFHC replacement. On one side, the continuation of the currently dominating timber frame mix, using chiefly timber light frame, called ‘average timber frame’ (ATF scenario), and, on the other side, the shift towards exclusively using more versatile, yet wood-intensive, cross-laminated timber frame (CLT scenario). A sensitivity analysis was conducted on the wood-based dwelling types to test the climate impact of changing the average Swedish dwelling size from the current 57 m² (SCB 2016) by ± 20% to either 68 m² or 45 m². The benchmark of the sensitivity analysis was keeping the concrete frame alternative constant at 57 m².

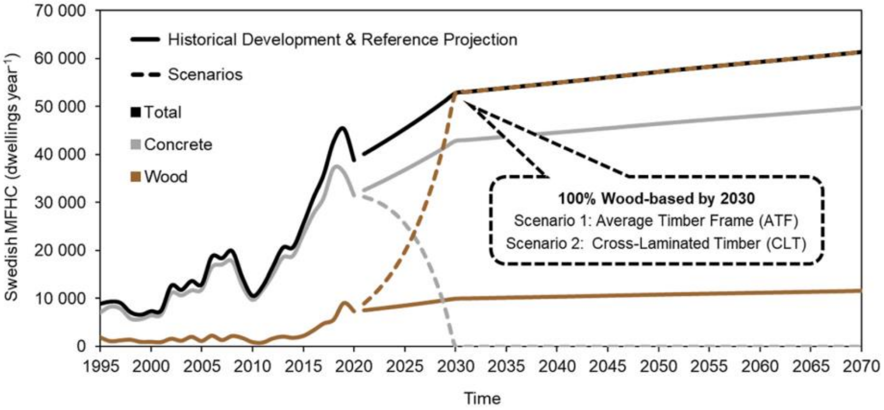

Figure 7 The annual historical multi-family housing construction and future reference projection, as well as scenarios given per frame material used (Paper III).

5. Results and discussion

5.1 Forest carbon stocks and balances

The simulated biogenic carbon stocks of Paper I and Paper II are displayed in Figure 8 and Figure 9, respectively. Independent of either of the biogenic carbon stock levels, the overall SOC comprises around two thirds of the total when considering a total rotation of either the Eucalyptus plantation (9 years) or the time horizon of the investigated Swedish forest regions (Norrbotten (north), Värmland (central), and Kronoberg (south)). In both Papers, the largest stock changes occur in standing biomass based on stem growth (carbon increase) and following harvest operations (carbon loss). Stock changes in SOC and dead wood are only minor, as was their role in climate impact. This pattern is especially apparent on the stand-level (Paper I), where general stock changes across the years are more pronounced. On the landscape-level (Paper II), the pattern is less pronounced and more evenly distributed. In the Swedish forests, the magnitude in the stock changes of biogenic carbon differ along a North-South gradient, the further south, the larger the magnitude.

The forest carbon stock modelling in Paper III and Paper IV relied on the same methodology used in Paper II, so the developments shown in Figure 9 are similar but apply for the whole productive forest land of Sweden (compare Section 4.2.2).

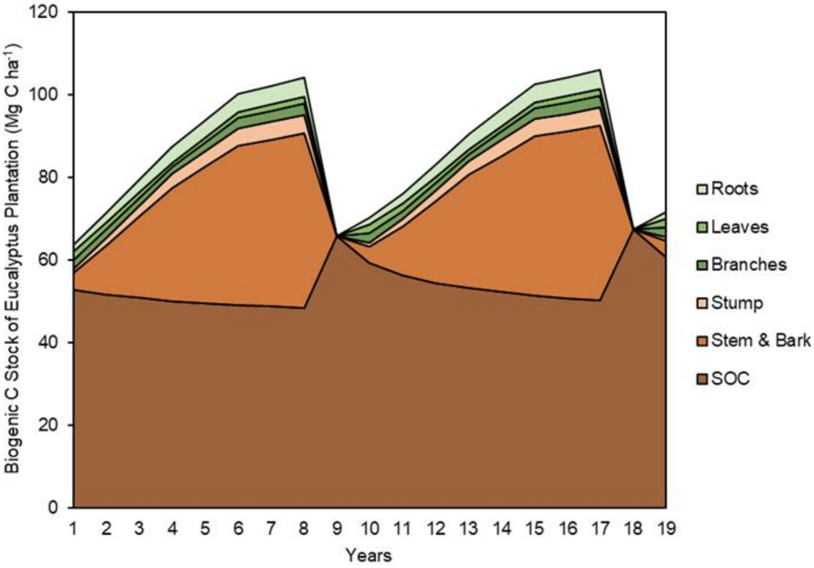

Figure 8 Biogenic carbon stocks from a stand-level in above and below ground biomass, as well as the soil organic carbon (SOC) of a Eucalyptus plantation (Paper I).

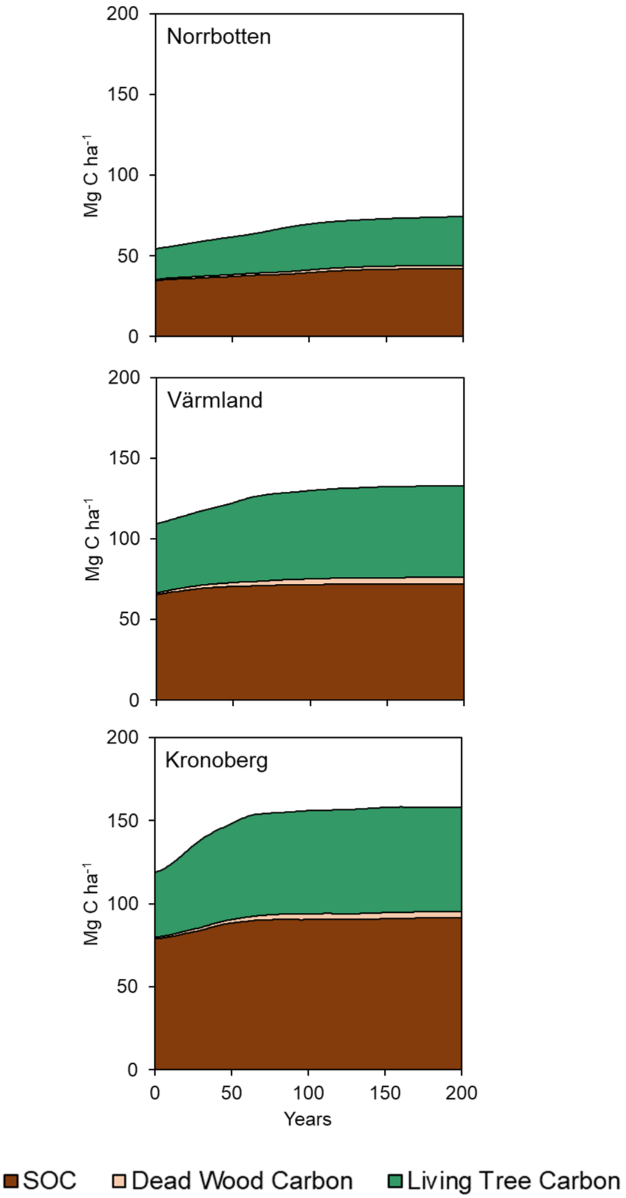

Figure 9 Forest carbon stock development from a 'real' landscape-level based on national forest inventory data from the Swedish regions; from north to south: Norrbotten, Värmland, and Kronoberg (Paper II).

5.2 Climate effects and climate change mitigation

5.2.1 Supply-driven forest-based systems

The main climate effect results for Paper I are given in Figure 10 and suggest a net emission sink, i.e., more emissions are either sequestered (biogenic carbon) or avoided (substitution effect) than are emitted (value chain emissions). This result implies that the supply of the beverage carton replaces a PET bottle, including the emissions from cradle to grave of the latter, as well as marginal energy sources. The material and energy substitution combined clearly contribute the most to this outcome, followed by the fossil value chain emissions and biogenic carbon, whose sink effect appears only minor. This contribution pattern arises mainly because the underlying forest system was modelled in a ‘theoretical’ landscape, and because of the functional unit and reference product chosen. The ‘theoretical’ landscape modelling is responsible for the biogenic carbon balance of the Eucalyptus plantation becoming ‘carbon neutral’ over time, since emissions following annual harvests are cancelled out by the yearly carbon sequestration from biomass growth (time-shifted single stand data). The functional unit is responsible for the magnitude of the substitution effect, since the fossil emissions of a PET bottle are larger than those of a beverage carton. As a consequence, the conclusion could be drawn that the more beverage cartons are produced, the larger the climate change mitigation created by substitution effects. However, this conclusion is misleading as it fails to account for the actual demand of how much packaging material is used for beverages and the share of PET bottles which could be effectively substituted.

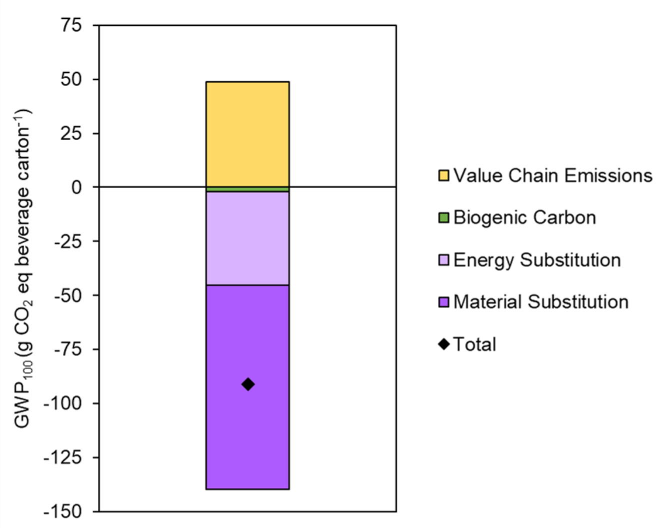

Figure 10 Climate impact of a beverage carton from a system perspective on the product scale following a supply-driven assessment approach, expressed in the global warming potential (GWP_{100}) (Paper I). Negative values indicate reduced GHG emissions.

Figure 11 presents an excerpt of the overall findings of Paper II. This is the climate impact from a system perspective of altering Swedish forest management in Kronoberg (southern Sweden) compared to the reference forest management. Changes in forest carbon stocks have a substantially larger climate effect, while those in HWP carbon storage and fossil GHG balance play a subordinate role. This may be due to the assumption that not all wood products replace a non-wood product (compare Figure 5 & Table 4). The overall outcomes highlight how a change in forest management aimed at increasing substitution effects (via shorter rotations, or increased harvest levels) does not lead to climate change mitigation in the short-term but to net additional emissions. In contrast, increasing the forest carbon sink (via decreased harvests and prolonged rotations) leads to climate change mitigation despite forgone (i.e., unrealized) HWP carbon storage and substitution effects.

A temporal trade-off is observable in either the longer or shorter rotation scenario and materializes in the form of a turn from sink to source or vice versa after around 40 years. For example, by prolonging rotations, the additional sink effect is given for the short-term only and in the long-term, this turns into a net source of CO_2 eq. The main reason for this is the average age class distribution of the forest in Kronoberg. In this region, as in the rest of Sweden, productive forestland is characterized by a comparatively young age. Accordingly, prolonging the rotation yields a generally larger climate effect than further shortening the rotations. Indeed, the average final felling age on productive forestland has decreased between 2009-2019 by 13%, from 113 to 100 years (SFA 2024). This trend of earlier final felling has decreased the current potential in Sweden for further decreasing rotation lengths in the future. However, it should be noted in this context that, thanks to decades of active forest management, the potential for an additional forest carbon sink by prolonging rotations exists, although this is limited to the short-term only. This is because prolonged rotations shift the baseline and can compromise additionality to other forest management in the future.

In Paper II, forest carbon is the driving force for the overall climate effects over time and also induces the temporal trade-off in HWP carbon storage and substitution effects. Meanwhile, the climate impact contribution of the latter plays a comparably moderate role similar to the fossil emission changes of the forest value chain. However, when rotations are prolonged, HWP carbon storage and substitution effects appear as an emission in the early years. This is because they are smaller than those in business as usual reference forest management. Accordingly, their contribution is ‘forgone’ (i.e., not realized). Concerning the substitution effects, this is especially prominent for pulpwood-based products such as packaging & textiles, which reflects how smaller diameter tree harvest is forgone following prolonged rotations. However, in the subsequent years, the sink of HWP carbon and substitution effects is larger than under the reference, thus contributes to mitigation. In particular, substitution effects from construction materials originating from larger diameter sawlogs are increased at this point, which reflects the silvicultural effect of extending the growing period of the forest. This trend is reversed (but smaller) under the scenario of shortening the rotation.

The results suggest that for Kronoberg, which comprises approximately 0.63 Mha productive forest land, prolonging rotations could, in the first 25 years, contribute to a mitigation of about 1 Mt CO_2 eq year^{-1}, which amounts to 2% of Sweden’s GHG emissions in 2021 (SCB 2023), considering the net sink of 1.6 Mg CO_2 eq ha^{-1} year^{-1} (Figure 11). However, in the long term of 100 years, this net mitigation is decreased to 0.2 Mt CO_2 eq ha^{-1} year^{-1}, which illustrates the aforementioned temporal trade-off. In general though, it should be noted that different forest management strategies with decreased forest use intensity affect the forest carbon sink in different ways. Accordingly, increasing rotation lengths, decreasing harvest rates, or increasing set-aside areas lead to different outcomes and should be assessed individually to gain insights about their respective climate trade-offs. In any case, a change in Swedish forest management is required in order to reduce the damages of climate change in the form of, for example, storms. Here, the adoption of alternative management strategies involving increasing shares of alternative tree species, other than spruce and pine, may be one option to reduce these impacts (Subramanian et al. 2019). Additional means are discussed in Section 6.1.2.

In Figure 12, the climate change mitigation outcome of Paper II is described as the average of the three investigated regions (Norrbotten, Värmland, Kronoberg). All four forest management scenarios under study are presented, giving the varying degrees of substitution effect on the market level (DF_m). Regardless of a higher or smaller substitution effect, the aforementioned outcome is supported. In the short term (2020-2070), reduced forest use intensity, in the form of decreased harvest rates or extended rotations compared to the current forest management in Sweden, yields climate change mitigation. On the contrary, a warming effect is given by increased harvest rates, regardless of the intensity of the substitution effect, in the form of the DF_m 0.2-1.4 Mg C Mg C^{-1}. In this context, Seppälä et al. (2019) found that to offset a loss in forest carbon from a 33% increased timber harvest in Finland, an average displacement factor of 2.4 Mg C Mg C^{-1} is needed. However, the authors further mention that the average DF_m is likely below 1.1 Mg C Mg C^{-1}, which presents a serious challenge for increasing harvesting in Finland – similar to the situation in Sweden.

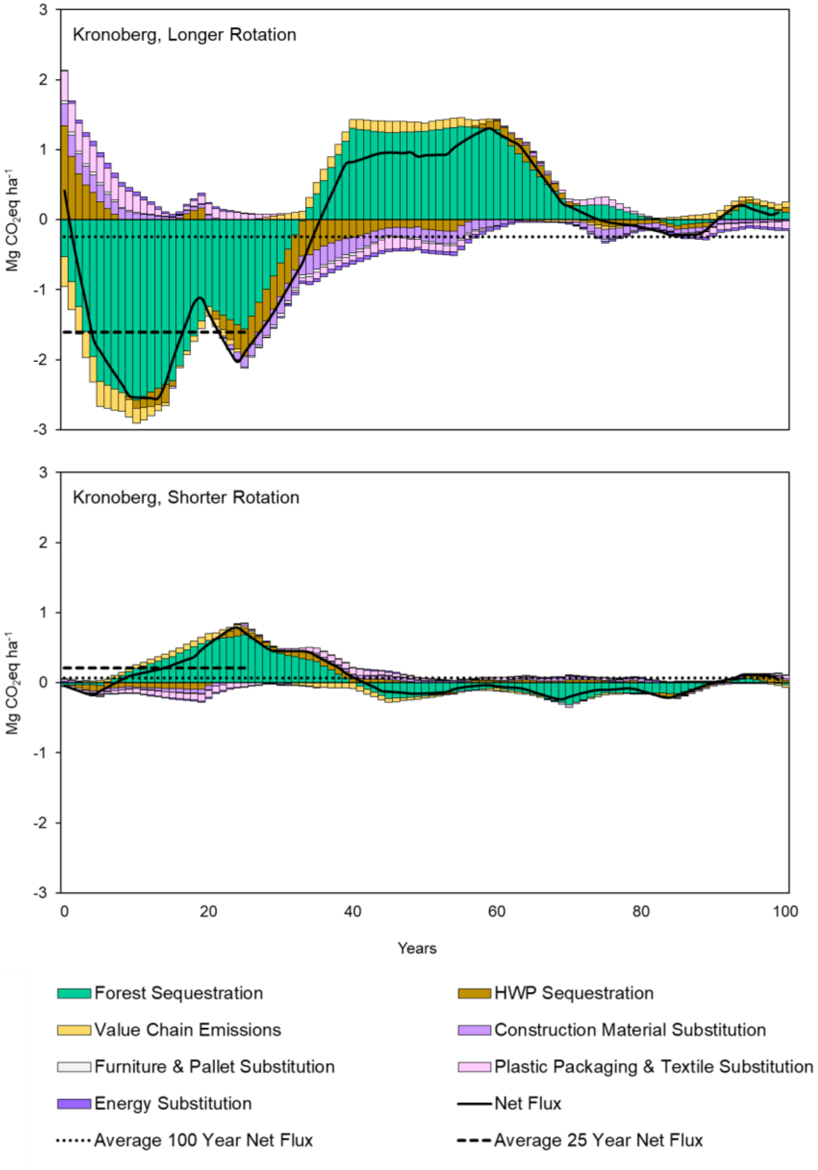

Figure 11 Annual climate impact of changing forest management towards a longer or shorter rotation for Kronoberg (southern Sweden), given in Mg CO_2 eq ha^{-1} (GWP_{100}), following a supply-driven assessment approach at the market scale (Paper II). Negative values indicate reduced GHG emissions.

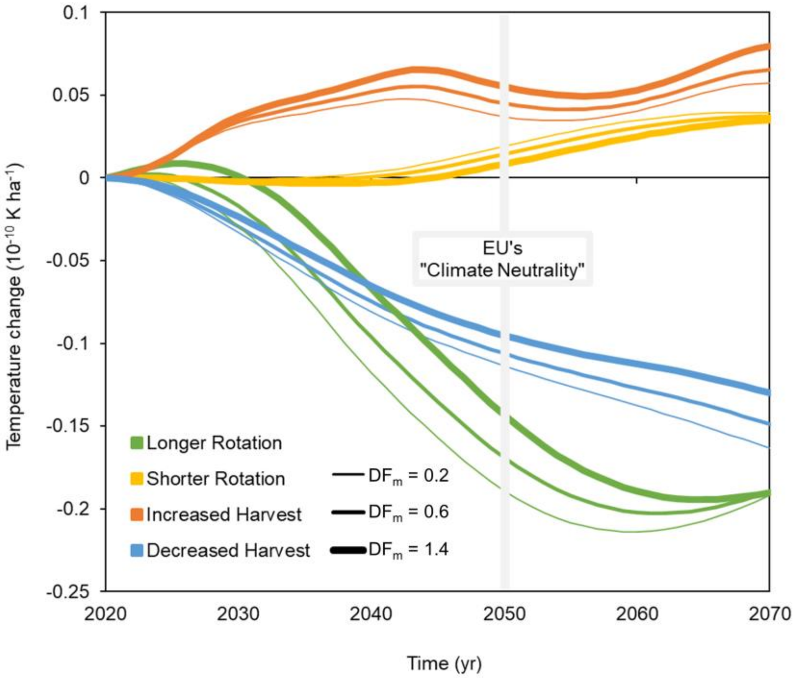

Figure 12 Climate impact of changing forest management as the average of three different regions in Sweden (Norrbotten (north), Värmland (central), Kronoberg (south)), in dependence to different market displacement factors (DF_m), expressed through the atmospheric temperature change given in K ha^{-1} (Paper II). Negative values indicate a climate cooling effect.

Figure 13 shows the cumulative GHG balances of Paper IV for the *Conservation* and *Substitution* scenario, as well as for the *Substitution+* scenario, which further includes the implications of by-products from dissolving pulp making. In general, all scenarios induce climate change mitigation in the form of a net cumulative sink of CO_2 eq, which is slightly larger under the *Conservation* scenario. This is chiefly based on the additional forest carbon sink, which over time increases and reaches a maturity state at the end of the time horizon (2100). In the *Substitution* scenario, avoided emissions from substitution with cotton fiber outweigh those from the additional production of dissolving pulp and MMCF. The *Substitution+* scenario shows that the consideration of the by-products from dissolving pulp making induces a slightly larger substitution effect potential and leads to increased HWP carbon storage, which contributes somewhat to an enhanced net sink effect.

Figure 14 presents the results from the sensitivity analyses of Paper IV. The largest climate change mitigation is achieved by the *Conservation* scenario, regardless of an improved availability of pulpwood following a changed pp-ratio. The second sensitivity analysis in Figure 14 presents how the *Conservation* scenario still outweighs the *Substitution+* scenario when the replacement ratio between MMCF and cotton fiber is decreased from 1:1 to 1:0.8. This represents that not 100% of the MMCF substitutes cotton fiber, but that a certain complementarity is given between the two goods. Indeed, MMCF being only a partial complement and not a full substitute for cotton fiber is supported by a recent econometric analysis (Hurmekoski 2024). The *Conservation* scenario would induce inferior climate cooling if a decreased pulplog saving efficiency under the *Conservation* scenario (-20% pp-ratio) and simultaneous improved dissolving pulp and thus MMCF availability, as well as the application of the by-products under the *Substitution+* scenario, is given (+20% pp-ratio). This would also happen if an ambitious replacement ratio between MMCF and cotton fiber of 1:1.2 was given. This highlights how concerted improvements across the industry are necessary in order to generate superior climate change mitigation from MMCF production than what can be currently achieved through reduced pulplog harvest activity. These improvements would need to comprise enhanced product properties and production efficiency, as well as demand changes for MMCF.

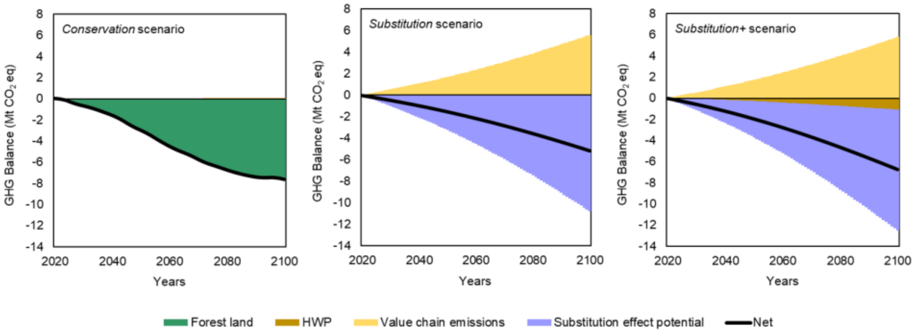

Figure 13 Cumulative climate impact of the *Conservation* and *Substitution* / *Substitution+* scenario making use of the exempt primary pulp amount from additional recovered pulp, given in Mt CO_2 eq (GWP_{100}) (Paper IV). Negative values indicate reduced GHG emissions.

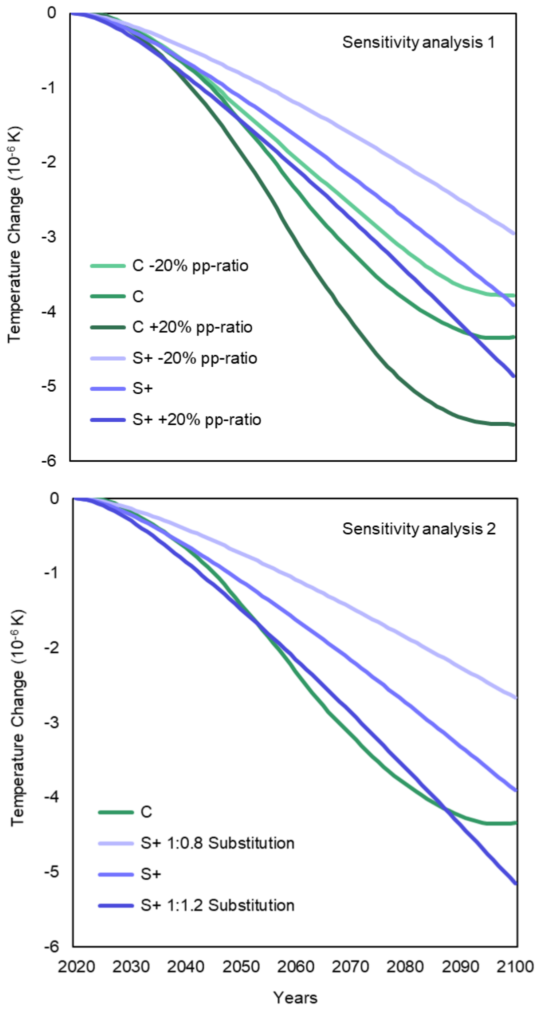

Figure 14 Sensitivity analyses of Paper IV.

Sensitivity analysis 1: Atmospheric temperature change in the *Conservation* (C) and *Substitution+* (S+) scenario including change of the primary pulp to pulplog ratio (pp-ratio) by ±20%. This implies changed pulpwood savings in the *Conservation* scenario and altered dissolving pulp, and thus MMCF and by-product availability, in the *Substitution+* scenario.

Sensitivity analysis 2: Atmospheric temperature change in the *Conservation* and *Substitution+* scenario including change of the substitution ratio of MMCF for cotton fiber by ±20%. This implies either partial complementarity between the two fiber types (1:0.8 substitution), or improved replacement conditions (1:1.2 substitution). Negative values indicate a climate cooling effect.

5.2.2 Demand-driven forest-based systems

In Figure 15 the GHG balance from replacement of the dominating concrete frames with either average timber frames (ATF), or cross-laminated timber (CLT) frame is presented (compare Figure 7). Overall, either of the national scale timber-frame scenarios yields a short-term net GHG sink effect relative to the continuation of the concrete ‘business as usual’ reference. This net sink effect is more strongly pronounced for the ATF scenario compared to the CLT scenario. For the latter, the net sink of the GHG balance ceases after 2040, whereas for the ATF scenario the net sink is generally maintained over the entire time horizon. This outcome is mostly due to the smaller loss of forest carbon under the ATF scenario as compared to the CLT scenario because the latter is more wood intensive in fulfilling the functional unit. In general, the loss of carbon in the Swedish forest is larger than the gain in HWP carbon storage, regardless of either the ATF or CLT scenario. This highlights that increased harvest activity for increasing the HWP carbon sink always comes with a decrease in the forest carbon sink, which risks outweighing the net additional gain, thus leading to a net loss of biogenic carbon (compare Figure 11). In the present case, this is the outcome even when considering the majorly long-lived wood materials used for MFHC. However, in the long run, the storage of carbon in wooden buildings is considered a viable carbon dioxide removal practice (Churkina et al. 2020). Alongside this, the additional fossil value chain emissions, entitled ‘Timber Dwellings’ in Figure 15, are clearly outweighed by the avoided fossil emissions from the ‘Concrete Dwellings’, meaning the replacement of concrete frame by either timber frame type induces effective substitution of fossil emissions, although this is limited by the amount of total MFHC.

It is not only the choice of materials that matters in the context of climate change mitigation. In addition to the question of which materials are used, the question of how much of each material is used in either housing type is equally important. This is reflected in the average dwelling size, which, in recent decades, has undergone a global growth trend (Ellsworth-Krebs 2020), contributing to growing environmental burdens (Ivanova and Büchs 2022). In Figure 16, the ‘Total’ from Figure 15 is shown in the form of the temperature change metric, as dependent on varying the future timber frame dwelling size by ±20%. The climate impacts here are again relative to the continuation of a ‘business as usual’ reference of concrete dominance which maintains the current Swedish average dwelling size of 57m² (SCB 2016). Clearly, smaller future living area induces a larger climate cooling effect. The ATF scenario generally leads to larger climate change mitigation than the CLT scenario. Even when an increase in the future living area is assumed under the ATF scenario, a net climate cooling effect is maintained. However, when the future average dwelling size under the CLT scenario is increased, the results suggest that climate cooling ceases, with slight warming even occurring. In other words, using CLT frame but building 20% larger dwellings yields a similar climate burden as continuing with concrete frame-based MFHC for a 57 m² dwelling size. This outcome highlights how for the substitution of concrete frame in MFHC, the increased use of the more wood-efficient ‘average timber frame’ (ATF scenario), which consists mainly of timber light frame, is to be preferred over a shift towards CLT frame (CLT scenario). However, CLT frame holds other advantages over the use of timber light frame because of its improved mechanical performance and dimensional stability (Hurmekoski et al. 2015) suitable for construction of high-rise buildings which require improved load-bearing capacities or more tensile strength compared to mid-rise housing options. The application of CLT frame could thus allow to reduce the extension of land sealing, especially in the planning of urban areas. This advantage is complemented by improved conditions for industrialized prefabrication to reduce on-site construction costs and GHG emissions. Together with principles such as ‘design for disassembly’, industrialized prefabrication using CLT, as well as timber light frame, can offer climate benefits at the end-of-life stage, as it enables the reduction of wood waste (Lehmann 2013).

The greatest climate change mitigation in future Swedish MFHC is achieved when coupling the already dominating timber light frame (ATF scenario) with a reduction in the average future dwellings size. This conclusion holds true when staying at the mid-rise building level. However, for high-rise buildings, a shift towards CLT in MFHC can be advantageous, under the constraint of not further increasing the average dwelling size. The results of Paper III thus highlight the climate benefits from increased use of wood in Swedish MFHC, while also revealing the limits to the climate benefit since it is constrained by the demand for the functional unit in question (‘living area’). This underlines the benefit of the demand-driven climate impact assessment approach in contrast to the supply-driven approach. In the latter, unrealistic outcomes can arise in comparable assessments, such as substitution effects based on an annual MFHC of 200,000-400,000 dwellings with 100m² (Gustavsson et al. 2017) compared to the 55,000 dwellings per year with 57m² found in the actual projected demand for MFHC in Paper III.

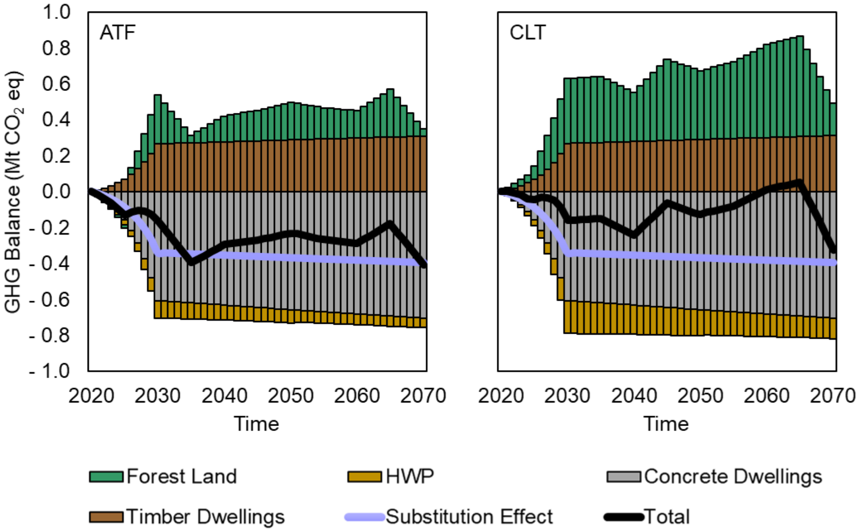

Figure 15 Climate impact of a demand-driven assessment approach for the case of multi-family housing construction in Sweden from 2020 to 2070, expressed in Mt CO_2 eq (GWP_{100}). ATF = Average timber frame scenario, CLT = Cross-laminated timber frame scenario (Paper III). Negative values indicate reduced GHG emissions.

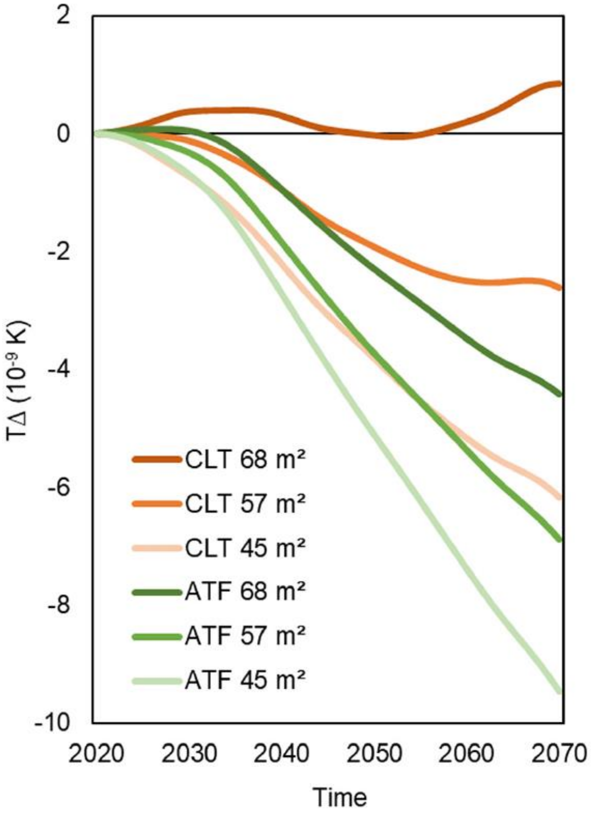

Figure 16 Climate impact of a change in average living area in future timber frame housing units as compared to maintaining 57m² as the average dwelling size in a concrete frame housing unit, expressed in atmospheric temperature change, given in K (Paper III). Negative values indicate a climate cooling effect.

5.3 Trade-offs with climate change mitigation

Trade-offs within forest-based systems do not only include those between different climate change mitigation measures. Since demand for forests and wood has been increasing for multiple functions, trade-offs also expand to resource availability or can concern environmental impacts other than global warming.

One example in this thesis is given in Paper III. Here the results suggest that a national scale replacement of concrete by timber as a frame material in MFHC yields climate change mitigation. The additional wood supply for meeting this demand is assumed to come from Swedish forests only. However, is there sufficient wood available in Swedish forests to supply a national upscaling of timber frame in MFHC? Table 5 compares the additional future demand of sawlogs necessary for upscaling timber frame in Swedish MFHC with the past Swedish sawlog harvest in equivalent timeframes. Indeed, regardless of the timeframe, only marginal amounts of additional sawlog harvest are required, mostly in the range of less than 1%. This highlights how – in a relative sense - only very small additional amounts of wood are required to realize either the ATF or CLT scenario of Paper III. However, in either case, additional sawlog harvests in Sweden may risk the felling of old forests (Swedish term: gammal skog (SCB and SLU 2023)), of which around 1.73 Mha remain in the country as of 2020 (excluding the formally protected forest areas) (SCB and SLU 2023). This is of great relevance since carbon storage (Weiskopf et al. 2024), or biodiversity-related ecosystem services tend to be greatest in old forests (Chaudhary et al. 2016; Mazziotta et al. 2022).

Paper IV provides another trade-off example with climate change mitigation. Here, the results suggest that conserving Swedish forests induces superior climate change mitigation instead of utilizing substitution effects via cotton fiber replacement. However, conserving forests may compromise other environmental impacts, such as water consumption. This is because water consumption tends to be high for cotton fiber production (Shen et al. 2010), which, through substitution with MMCF, could be decreased while it remains forgone under the *Conservation* scenario. On the other hand, if production of MMCF and substitution of cotton fiber is chosen instead of conserving forests by reducing Swedish pulpwood harvest, a climate-biodiversity trade-off could apply, as mentioned for Paper III. However, pulpwood harvest may not be as likely or frequent as sawlog harvest in old forests, for example, due to demanded log diameters. In summary, both the trade-offs solely *within* climate change mitigation and trade-offs *with* climate change mitigation ought to be taken into consideration when designing measures to reduce global warming in forest-based systems.

Table 5 Future demand in Paper III within the ATF and CLT scenarios for sawlogs from Swedish forests and past Swedish sawlog harvest, illustrating the very small relative additional supply needed. Numbers shown are cumulative over the respective time horizon.

Future or past years, relative to 2020	Future cumulative sawlog demand (Mm³ under bark)		Past cumulative sawlog harvest in Sweden (Mm³ under bark)
	ATF scenario	CLT scenario	
10	1	1	388
30	7	9	1030
50	13	17	1494

6. General discussion

In the following, the results presented in this thesis are discussed from a more general perspective. First, as to how the different assessment scales and approaches have influenced the results and the conclusions that may be drawn, and second, as to the degree to which mitigation could be achieved from the results. Finally, uncertainties and limitations connected to the results are discussed.

6.1 Towards climate change mitigation in forest-based systems

6.1.1 Scales and assessment approaches

A system perspective was applied in each assessment which underlies this thesis as this is a sound basis for robust decision making on climate effects of complex forest-based systems (Cowie et al. 2021; EC 2021a; Rüter 2023). In addition, a distinction between a supply-driven and demand-driven assessment approach was made, which could be applied to either a product or market scale. This distinction was based on the observed structure of past climate impact assessments of forest-based systems, including those which underly this thesis. Therefore, each assessment approach and scale bring advantages and disadvantages, which are discussed in the following, focusing on the results of Paper I-IV.

The main results of Paper I suggest that following a supply-driven product scale assessment, the use of a beverage carton over a PET bottle induces climate change mitigation, irrespective of the replacement ratio or the marginal energy mixes which were assumed to be avoided. This outcome serves as an example of how a promising wood product can contribute to the reduction of global warming, given that its production and use verifiably substitutes for production and use of the counterpart product. The assessment of Paper I is an example of how time-dynamic LCAs from a system perspective should be conducted to understand product specific climate performance, including the substitution effect. The supply-driven product scale applied here is thus well suited, for example, to test the implications of different assumptions around system boundaries and land use baselines in forest-based systems, as done by Peñaloza et al. (2019). However, upscaling the outcomes from the product scale for use on regional or national level climate assessments should not be done. This is because the results suggest that, due to the substitution effect offsetting all remaining emissions, the more beverage cartons that are produced and used, the larger the benefit for the climate. A misleading logic which was used for greenwashing purposes, in an example where instead of the substitution effect, carbon credits from afforestation projects were used to "offset" all the emissions associated with the "cradle-to-customer" emissions (UNFCCC 2019) to sell a "climate positive" product. This is a logic which serves to justify business-as-usual corporate climate approaches, enabling and legitimizing a carbon-intensive lifestyle, and risks diverting from decarbonization efforts (Christiansen et al. 2023).

In Paper II, a supply-driven market scale assessment approach was applied. The main outcome here confirmed results of a body of previous studies showing that within a short to medium term, the climate benefit from the forest carbon sink exceeds additional mitigation from substitution effects and increased HWP carbon storage (Lundmark et al. 2014; Matsumoto et al. 2016; Valade et al. 2018; Seppälä et al. 2019; Kalliokoski et al. 2020; Soimakallio et al. 2021; Jonsson et al. 2021; Skytt et al. 2021; Moreau et al. 2022; Soimakallio et al. 2022; Schulte et al. 2022), regardless of the intensity of the assumed substitution effect. However, in the abovementioned studies, the additional or reduced quantity of wood products was merely steered by assumptions regarding forest management. This approach risks communicating unreasonable substitution effects, since often no demand accounting of the various functions for which the wood products are assumed to replace non-wooden counterparts is given. The question 'What material has which share fulfilling the function under question today, and what is the projected demand of the function in the future?' is neglected in supply-driven market-scale assessments, which make use of product-scale results such as those of Paper I. The supply-driven market scale is well suited to test ‘what if’ scenarios concerning e.g., a change in forest management, but bears shortcomings as to substitution effect estimations. Like the example mentioned under Section 5.2.2, this can lead to unrealistic outcomes which base substitution effects on an annual Swedish MFHC of 200,000-400,000 dwellings (Gustavsson et al. 2017) as compared to the officially foreseen 55,000 dwellings per year (Boverket 2021).

Indeed, the demand projection for MFHC in Sweden in Paper III served as a safeguard to ensure no overestimation of possible substitution effects and indicated a more realistic impact of increased wood demand on Swedish forests. The outcome of the study suggests that the replacement of dominating concrete frames in Swedish MFHC with timber frames induces slight climate change mitigation with only minor impacts on Swedish forest resources. This type of assessment approach was conducted, for example, by Hafner and Rüter (2018) for German housing yet remains rather unexplored. The demand-driven product scale approach is well suited for targeted case studies assessing the climate impact of a changed material or energy use for meeting the demand of a certain function. The approach avoids the overestimation of substitution, other than uncertainties related to underlying LCI data or material inventories and enables estimation of the implications for biogenic carbon balances in HWPs and forests.

Paper IV suggests that decreasing the pressure on Swedish forests yields larger climate cooling effects instead of producing additional MMCF, which could substitute for cotton fiber. This outcome is based on a hybrid approach from ‘*fiber to forest or function*’, mixing mostly supply-driven, but also demand-driven, aspects and assuming increased paper recycling as compared to today’s recycling rate. It comes to this outcome because the increased forest carbon sink under the *Conservation* scenario outweighs the alternative of an additional substitution effect potential under the *Substitution+* scenario. Consequently, the results are strongly dependent on both the modelled forest baseline, which in Sweden is characterized by a relatively young forest age class distribution (compare Table 3), and on the product scale LCI data used for the MMCF and avoided cotton fiber. A hybrid approach departing from a point along the forest value chain may be suitable to increase the understanding about possible climate change mitigation from additional recycling activities of alternative wood uses.

It may, at first glance, seem like the results of Paper II and Paper IV, and those of Paper III contradict each other. This is because they provide different conclusions as to whether increased or decreased Swedish forest use is superior for climate change mitigation in Sweden. Paper II and IV both indicate that decreasing harvest levels induces more climate change mitigation, with Paper II even finding increased harvests yielding to a net warming effect. In contrast, Paper III finds increasing harvests yielding climate benefits. This outcome arises because the net climate benefit from increasing wood harvests achieved in Paper III relies on a more climate-effective wood use compared to that of Paper II. In principle, different system boundaries apply so that substitution in Paper II occurs on the market scale, while in Paper III it is limited to the product scale. This means that in Paper III, a function is considered for which mostly long-lived wood products are used (MFHC), which improves the general climate performance. In contrast, in Paper II, a substantial proportion (47%) of the increase in harvest does not cause substitution or belongs to wood products serving functions for which only small lifetimes are needed (see Figure 5) – a condition which leaves great potential for improving efficiency and climate change mitigation in the Swedish forest sector.

6.1.2 Component contribution

The overall magnitude and individual contribution of the carbon sink in forests and harvested wood products, fossil value chain emissions, and the substitution effects can differ depending on the modelling approach and the scale chosen. However, regardless of the approach or scale applied in Paper I-IV, the forest carbon sink shows the most important contribution to climate change mitigation in the short to medium-term (i.e., 50-70 years). Hence, forests were the most important contributor to the climate impact when altering forest management (Paper II) when considering national upscaling of timber frames in MFHC (Paper III) or concerning additional paper recycling for climate change mitigation (Paper IV). Only on the supply-driven product scale (Paper I) did the contribution of the forest system appear to be inferior, which is due to the modelling choice of a ‘theoretical landscape’, as explained in Section 5.2.1, and the fact that a short-rotation forest system was given. The storage of carbon in HWPs is, in comparison to the forest carbon, of inferior importance to the climate effects, regardless of the studied system in Paper I-IV. This pattern is reflected in the magnitude of the HWP carbon sink relative to that of the forest carbon sink within the Swedish and EU LULUCF-sector.

The contribution of the substitution effect to the overall climate impact is, however, a more uncertain factor. How large is the substitution effect in comparison to the forest and HWP carbon sink? In the case of Sweden, different assumptions about if and to what extent wood products substitute fossil fuels and products have made studies differ on whether harvesting more (Gustavsson et al. 2017; Gustavsson et al. 2021; Petersson et al. 2022) or less (Skytt et al. 2021; Schulte et al. 2022; Eriksson et al. 2024) is beneficial for the climate. A fundamental question is the quantity of wood that replaces fossil products and energy. One option is to assume that all the harvested wood leads to the replacement of fossil-based products, such as concrete or plastics, considering aggregated, semi-finished, wood product groups. However, this approach greatly overestimates the substitution effect. As an example, the Swedish forest industry federation (Skogindustrierna) presents very large substitution effects, currently at 72 Mt CO_2 eq year^{-1} (SFI 2024), which amount to 1.5 times the total fossil GHG emissions of Sweden in 2021 (48 Mt CO_2 eq year^{-1}) (SCB 2023). Similarly the substitution effect of the EU forest-based sector was stated to be 390 Mt CO_2 eq year^{-1} (AFRY 2024), which is 1.7 times the net EU LULUCF sink of 230 Mt CO_2 eq year^{-1} (EEA 2023a). As substitution is a relative concept (Section 3.2.4), it requires the definition of a realistic baseline. In the above examples, i.e., SFI (2024) and AFRY (2024), the implicit baseline represents the non-existence of the forest-based sector, which is a questionable assumption because it is unlikely that the Swedish or EU forest-based sector, respectively, will disappear within the foreseeable future. Estimates of this type do not represent an actual substitution effect, but a substitution effect *potential*. Communicating such large effects of substitution can promote production of wood products which may not replace more emission-intensive counterparts on the market and thus risk to merely contribute to a net addition of GHGs in the atmosphere.

The correct approach is to consider substitution effects only insofar as end-uses, meaning finished wood products, are concerned. Increasing the degree of detail in the assessment thus provides a more accurate substitution effect estimate compared to the other approach. If demand accounting for the products is done, then the substitution effect additionally receives a cap. This accounting needs to also include consideration of whether, and to what degree, both wood products and their avoided alternatives are substitutes. This includes econometric analysis accounting for own price and cross-price elasticities of the wood products and their counterparts, as stated in Section 3.2.4. Ultimately, the magnitude of the substitution effect is thus smaller than frequently communicated because (i) wood flows and (ii) replacement ratios between wood products and counterparts are assumed too optimistic, (iii) the LCI emission data applied is too general, and (iv) key assumptions concerning the wood products' demand are not accounted for.

6.1.3 Mitigation magnitude

The climate impact results of all Papers in this thesis focus on Sweden. It is therefore reasonable to compare the outcomes with the total fossil GHG emissions of Sweden to better understand their relevance and contribution to the design of climate change mitigation measures. To reduce the uncertainty connected with the following comparisons, only short-term results (<30 years) are put into context. In Paper II, the possible mitigation from prolonging rotations of about 1 Mt CO_2 eq year^{-1} within the first 25 years, as mentioned above in Section 5.2.1, amounts to 2% of Sweden's GHG emissions in 2021 (SCB 2023), and comprises solely the regional (!) effects of Kronoberg (where around 3% of all productive forest land in Sweden is located (SCB and SLU 2023)). This is about four to ten times greater than the national (!) mitigation potential found in Paper III, which ranges in the first 30 years from 0.23 Mt CO_2 eq year^{-1} to 0.11 Mt CO_2 eq year^{-1} for the ATF and CLT scenarios, respectively. This comprises 0.5-0.2% of the annual total GHG emissions in Sweden during the year 2021 and is a similar magnitude as the results from Paper IV, where the GHG mitigation in the first 30 years is 0.06 Mt CO_2 eq year^{-1} to 0.1 Mt CO_2 eq year^{-1} for the *Substitution+* and *Conservation* scenario, respectively. This overall pattern of mitigation magnitude in Papers II-IV, in which changes in forest management offer considerably greater mitigation than changes in wood use, supports the conclusion of a previous meta-assessment (Verkerk et al. 2022) on studies that investigate possible mitigation measures of the forest-based sector.

In fact, when considering prolonging rotations across all three studied regions in Paper II (Norrbotten: 0.7 Mg CO_2 eq ha^{-1} year^{-1}, Värmland: 0.9

Mg CO_2 eq ha^{-1} $year^{-1}$, Kronoberg: 1.6 Mg CO_2 eq ha^{-1} $year^{-1}$) and upscaling the effect by means of the area-weighted average to the entire forest area for wood supply in Sweden (virkesproduktionsmark), which amounts to approximately 19.7 Mha (SCB and SLU 2023), the overall additional climate change mitigation potential would be 16.6 Mt CO_2 eq $year^{-1}$ in the first 25 years. This is four times what is required to meet the additional Swedish LULUCF Member State target sequestration of 4 Mt CO_2 eq $year^{-1}$ by 2030 and thus corroborates the substantial forest carbon sequestration potential from prolonging rotations. In addition, it underlines the great potential of the Swedish contribution to additional mitigation potential in the carbon carrying capacity of European forests estimated to be 309 Mt CO_2 eq $year^{-1}$, which is about 11% higher than the current forest carbon sink (280 Mt CO_2 eq $year^{-1}$) and comparable to the EU LULUCF target for 2030 (310 Mt CO_2 eq $year^{-1}$) (Keith et al. 2024). It also highlights how prolonging rotations, next to restoration and sustainable management of more diverse forests to enhance forest resilience (Felton et al. 2024), would reduce the pressure on increasing harvest supplies from Swedish forests, thus avoiding a trade-off between EU climate targets (LULUCF) and adverse effects on multiple ecosystem services and biodiversity (Blattert et al. 2023; Mo et al. 2023).

6.2 Methodological aspects and uncertainty

6.2.1 System boundaries

Quantifying the climate effects of forests and wood use relies on models. However, every model is only an approximative representation of reality and is therefore always characterized by a trade-off of modelling choices and subjective assumptions made by the modeler. Therefore, transparent communication of the assumptions in forest-based systems is crucial for understanding the relevance of the results obtained, not only in the context of bioenergy where this discussion was held before (Giuntoli et al. 2020).

One important modelling decision concerns the definition of the system boundaries of the assessment. The spatial boundaries in Paper II and III focused on Sweden, while those of Paper I and Paper IV extended over Sweden and also included Uruguay or China, respectively. This primarily had effects on the fossil value chain emissions and choice of the appropriate

LCI data. However, the impact of the geographical setup did not have a major influence on the results of the Papers.

The temporal system boundaries must be decided using the appropriate time horizon. Here, a general trade-off is present between a short-term or long-term focus, exemplified by Figure 11, Section 5.2.1. Short-term time horizons highlight the need for immediate action to avoid overshooting climate thresholds (Paris agreement) (Røyne et al. 2016), but disregarding long-term time horizons disguises information about, for example, climate effects affecting intergenerational justice (Peñaloza et al. 2019). However, long-term temporal system boundaries generally add sources of uncertainty, such as those concerning the development of the fossil emission profiles of products, end-of-life scenarios, or the general choice of benchmark products.

6.2.2 Forest system

Methodological aspects concerning the climate impact of the forest system are numerous. A key modelling choice for the forest system is the definition of a valid reference scenario representing baselines of land use and harvest levels to guarantee the appropriate additionality of the assessment (Røyne et al. 2016; Peñaloza et al. 2019; Chomitz 2002). In Paper I, the land use baseline of the Eucalyptus plantation in Uruguay was grassland where no harvest was assumed to occur. In Paper II-IV, the land use baselines were productive forest lands in Sweden. These were either based on the FRL, with a harvest intensity of 83% with a reference period from 2000-2009 (Paper II), or on SKA22, with harvest intensity of 79%, which itself was based on NFI-data with a reference period from 2011-2015 (Paper III & IV). The land use baseline is also determinant on the effects of albedo, another influence on the climate effects of forests, as mentioned in Section 3.1. Indeed, albedo offsets are considered to be especially high in boreal settings (Hasler et al. 2024) yet have only shown minor impacts in altering radiative forcing compared to CO_2 (Kalliokoski et al. 2020).

Forest carbon leakage is another influential factor able to compromise a net climate benefit from, for example, reduced forest management intensity (Paper II). However, throughout the assessments included in this thesis, international leakage effects were not accounted for. This was because the spatial system boundaries excluded associated effects (Paper I, II), increasing of harvests was assumed to only occur within Sweden (Paper III), or net harvest levels were not decreased so that harvests elsewhere did not have to compensate (Paper IV). However, in the context of Paper II this is a limitation, because international and interregional leakage effects within Sweden could compromise the regional climate benefit from extending rotation lengths or reducing harvest levels. In both contexts, Lundmark (2022) highlights that when assessing interregional (subnational) leakage, additional data is needed, while internationally, a reduced harvest scenario of 20% would induce leakage effects of up to 27% for sawnwood, 53% for pulpwood and 72% for firewood, as mentioned in Section 3.3.2. At the EU level, a reduced felling of 20% is further estimated to result in a leakage of 79%. In general, leakage is higher in the short term than in the long term, which emphasizes the impact for short-term climate benefits from prolonging rotations.

The accounting approach of biogenic carbon plays another influential methodological role. In the past, many assessments counted biogenic carbon as ‘carbon neutral’ (Pawelzik et al. 2013), comparable to how bioenergy is officially reported under the UNFCCC (Cowie et al. 2021), where formerly sequestered carbon by forest growth is released instantaneously at the point of tree harvest and no emission is accounted for in the energy sector. However, natural time-dependent dynamics of biogenic carbon are now increasingly considered in climate impact assessments of forest-based systems, which capture physical reality to a better extent. Here, the approach and data used to model forest carbon dynamics, as well as the storage of biogenic carbon in HWPs, can significantly influence the outcome of the assessment (Peñaloza et al. 2019). The accounting of forest-based CH_4 or N_2O emissions from, for example, harvest activities and soil preparations (Vestin et al. 2020), further completes the full GHG fluxes occurring in forest systems.

The overall outcome of an assessment from a system perspective is moreover heavily dependent on the sophistication of the underlying forest model and the quality of its data and functions. The Swedish NFI provides a sound data source for national forest assessments as it has been conducted for more than a century with about 11,000 sample plots being inventoried each year (SCB and SLU 2023). However, to provide robust information as to how forest management needs to change to enhance climate change mitigation and resilience, timely data is needed. Until now, national GHG inventories are frequently based on data which are collected periodically (e.g., in 5-year cycles) causing a lag of several years or more than a decade between measuring and reporting changes in the forest carbon sink. This lag is increasingly problematic as it gives belated feedback both on the consequences of forest management and on the overall strength of the sink (Korosuo et al. 2023).

In addition, more research, knowledge, and development are still required when aiming to consider the consequences of climate change on the forest (eco-)system in forest models such as Heureka. Boreal forests are on average considered to increase their resilience as a beneficial consequence of warmer temperatures and CO_2 fertilization, although this faces local variability (Forzieri et al. 2022). On the other hand, the number of tree species which can be planted today, and which would stay within their climatic niche throughout the entire twenty-first century is declining (Wessely et al. 2024). This implies that the average species mix in Sweden, being largely spruce dominated, is not suitable for the 21st century, while connected losses through the next decades are considered to be some of the highest in Europe. An associated decline in the forest carbon sink in (European) boreal forests has been reported to have already taken place during 1990-2020 (Pan et al. 2024). In Sweden, the forest growth decline of the past decade (Laudon et al. 2024), is suspected to continue the trend of forest carbon loss (SFA 2023). In the future, Swedish forests can thus experience both growth enhancing (higher temperatures and more precipitation) or detrimental (bark beetle outbreaks, windstorms, forest fires, or other infestations) consequences (Subramanian et al. 2019). Until now, however, with the exception of storm occurrences, only growth enhancing factors can be accounted for when running Heureka (version 2.22.0.0). This is why the impacts of climate change on Swedish forests were excluded in Papers II-IV to guarantee a more conservative assessment.

When it comes to impacts of climate change on the forest, it remains important to state that this has feedback effects also for global warming itself, for example in form of increased mortality. In this context, climate adaptation plays an increasing role in the mitigation measures taken in order to reduce the risk of damage from natural disturbances (SFA 2023). Some mitigation measures in the context of this climate-smart forestry approach (Nabuurs et al. 2018) are summarized for the Swedish case by a recent assessment from the Swedish Forest Agency (SFA 2023). Here, reducing browsing damage was shown to offer long-term advantages for increasing the forest carbon sink. In contrast, simulations of continuous cover forestry (CCF) suggested no major changes compared to current Swedish forest management in terms of forest carbon sequestration. Caution is advised, however, when interpreting these results as the ingrowth modelling under CCF requires further development. Results on nitrogen fertilization to increase growth and, hence, the forest carbon sink, suggested limited effects, although this measure was previously indicated to be a viable mean to increase increments (SFA 2014b), especially in northern Sweden where nitrogen availability in forests is low (Karlsson et al. 2022). Moreover, increasing set-aside areas indicated no increased net carbon sink if the remaining productive forest land is used more intensively to maintain the current felling volume. Simulations of an increased proportion of broadleaved trees in the form of birch suggested even a reduction in the forest carbon sink because of decreased tree growth. However, the positive effects more broadleaves (including species other than birch) could bring for climate change mitigation as well as adaptation remains to be studied.

6.2.3 Technosystem

Uncertainties and limitations within the technosystem include few regionally specific LCI data (Paper I-IV), reliance on only a limited (and thus barely representative) number of material inventories (e.g., for concrete or timber frame dwellings) (Paper III), hitherto incomplete data on wood end uses and their respective shares among the total amount of wood use (Paper II), the missing extension of the system boundaries to include the international trade of wood and wood products at the market level (Paper II), and the reliance on sawlog or pulpwood reference harvest levels provided by simulations of partial equilibrium models such as GLOBIOM (Havlík et al. 2018; Lauri et al. 2021) (Paper III, IV).

The uncertainty of the substitution effects deserves special emphasis since their contribution from a system perspective can decide whether a forest-based system induces net climate change mitigation, or not (see Figure 15, Section 5.2.2). In general, substitution effects depend on the share of wood being assumed to substitute for more emission-intensive products, the reference product, or forest use intensity (management), and a supply-driven or demand-driven approach (no substitution limit vs. substitution limit), as mentioned before.

Substitution occurs on the product scale and is linked to the fulfilment of a functional unit for which product scale LCAs are required to estimate the associated environmental consequences. In this context, the concept and use of displacement factors is frequently used for estimating the substitution effect, but this use is often criticized. This is because relating the GHG emission saving potential between a wood product and its alternative to the biogenic carbon contained in the wood product (compare Section 3.2.4) ultimately contradicts the central principle of LCA, which is to relate the environmental impact exclusively to a defined functional unit (Rüter 2023) and not to the amount of biogenic carbon in HWPs. The consideration of substitution effects via displacement factors may seem intuitive and simple and shows a major positive effect on wood use when scaled up (Sathre and O'Connor 2010; Leskinen et al. 2018; Myllyviita et al. 2021), but the estimated substitution effects by means of displacement factors are purely hypothetical, as they are based on many assumptions which are often unrealistic. For example, it is assumed implicitly that the demanded quantity of goods and services to fulfil one or more functions is identical in either wood or non-wood alternatives, which means that substitution in any direction has no impact on prices, quantity ratios or availability. This shortcoming makes the results of an analysis based on displacement factors uncertain and prevents them from being directly linked to official GHG inventories (Rock and Rüter 2023), such as the official reporting to the UNFCCC. Alongside this, some wood product comparisons are in general hardly compatible with the principle of functional equivalence, as can be seen with the example of furniture. Here, it becomes apparent that next to the actual function of the product, there exist other criteria which are relevant for demand, such as the aesthetics of the furniture item. If recycling aspects are added to the definition of functional equivalence, for example, recycled paper substituting an e-reader, substitution assessments of certain wood use based on the functional unit are barely feasible.

Even if more detailed LCI data and better demand accounting were available, the increasing ambitions to meet political climate targets may continue uncertainty around future substitution effects. This is because of decarbonization efforts in the forest-based sector and in other industries. In this context, the substitution effects from wood product use may decrease in the future, for example, due to general decarbonization of the energy sector and increased recycling of construction materials (Myllyviita et al. 2022), or in cases where emissions are set in alignment with the Paris agreement (Rockström et al. 2017; Brunet-Navarro et al. 2021). Noteworthy in this context is the European Trading System (ETS) of the EU. The ETS serves as an instrument to cap or limit fossil GHG emissions per sector in each participating Member State through carbon allowances which must be followed and can be traded, and whose number is continuously decreasing over time (Lilica and Drury 2023). For the substitution effects of forest-based systems, this implies their reduction, for example, through (‘green’) steel replacement (Zhang et al. 2021). On the contrary, efficiency improvements within the forest-based sector have the potential to increase the substitution effect of wood use (Myllyviita et al. 2021), for example, via recycling and enhanced cascading. Improved substitution effect estimations are desirable in this context which take technological and decarbonization developments into account. Here, the use of prospective LCA, which couples dynamic LCA methodology with scenario modelling of Integrated Assessment Models (IAMs) based on, for example, shared socioeconomic pathways (SSPs), offers promising exploration options (Sacchi et al. 2022).

Several standardization efforts are currently underway for climate impact assessments (of forest-based systems) which are increasingly used, for example, by the corporate sector. The standards aim to guarantee comparability among the results by harmonizing the accounting approach, for example, for products used in the construction sector. Examples include the Environmental Product Declarations (EPD) (EPD 2024), the Product Environmental Footprint (PEF) (EC 2021c), the Science-based Target initiative (SBTi) (SBTi 2024), the GHG Protocol (GHGP 2004) and the ISO 13391 series currently under development (ISO 2024). However, the standardization efforts require further scientific guidance especially concerning a universal accounting approach for biogenic carbon (GHGP 2024), and an appropriate estimation of substitution effects (ISO 2024). This need for more knowledge concerns not only methodological aspects but also emerging wood products, such as lignin-based applications. In this context, it is important that the industry invests in innovations to achieve greater climate benefits than those of the current portfolio of wood products.

6.3 The way forward for an effective mitigation debate

From a political perspective, achieving intersectoral climate change mitigation represents a contradictory situation. On the one hand, energy and other industrial sectors are required to lower their GHG emissions, for example, by boosting the use of (wood) biomass, thus exploiting substitution effects, to achieve climate neutrality. On the other hand, the LULUCF-sector must enhance its climate change mitigation efforts by either stockpiling biomass in forests, and thus retaining it for other sectors' use, or by enhancing the sink in HWPs. This general climate trade-off has formed a pivotal motivation for this thesis and the underlying Papers. To this end, it remains to be stated that the general debate about forest-based climate change mitigation needs to be steered away from what and how much mitigation forests and the associated sector can achieve. Instead, the debate should focus on questions regarding the functions, services and functionalities required in society, and how forests and wood uses can contribute to these. This needs to be accompanied by sharper policies which cut across forest, industrial, and climate policies in a coordinated way, combined with effective instruments that harmonize policies with the set climate goals (Rummukainen 2024). This includes enhanced information and advice from authorities to forest owners, compensation for enhanced carbon sinks, or support for measures that provide synergies between climate efforts and nature conservation. Moreover, an intersectoral GHG budget orientation in terms of climate protection can be more advantageous than individual sectoral targets, for example, for the steel making industry, the forest industry, etc. Through this, substitution effects will also materialize. In the context of the MFHC example of Paper III, this means, for instance, that the first question to be addressed is that of sufficiency: are the additional flats projected in the housing construction forecast really needed? If the answer is yes, then the realization of this societal requirement should be as climate-friendly as possible, which in this example is associated with a decreased dwelling size and an increased use of wood compared to current practices. The GHG emissions associated with the realization of this societal function would then have to be counted towards the overall intersectoral GHG budget and not a sector target (Rock and Rüter 2023). Forest resources are renewable but limited and increasingly demanded. Due to their capacity to support climate change mitigation, the pressure on systems including forests and wood is increasing. The principle of focusing on societal needs and their fulfilment could thus also be aligned to the EU waste hierarchy approach of, reduce, reuse, recycle (EU 2008), emphasizing the importance of sustainable material handling in societies towards 2050 and beyond.

Ultimately, and in the context of overall sustainability, it remains important to note that future decisions in the forest-based sector should be steered towards the fulfilment of broad societal requirements - a balance between timber production, biodiversity conservation (Felton et al. 2016; Eggers et al. 2020), recreation (Eggers et al. 2018), and other ecosystem services, - and not solely the maximization of climate change mitigation.

7. Conclusions

Methodology

A system perspective is required to correctly understand whether forests and the use of wood leads to climate change mitigation. This includes four components: forests, wood products, forest value chain, and substitution.

The outcomes of climate assessments following a system perspective vary based on whether a product or market scale is applied and whether they follow a supply-driven or demand-driven approach (with hybrid versions also being possible). Appropriate baselines (land use, replaced material, etc.) should be defined and aligned to the functional unit of the climate impact assessment.

The forest carbon sink accounts for the most significant climate change mitigation contribution of all the components of a system perspective. This is due to (i) its role as foundation of forest-based systems, (ii) its sequestration role via photosynthesis, (iii) its overall mitigation magnitude compared to the other components (HWP, value chain, substitution), and (iv) the risk for deterioration due to global warming.

Substitution effect estimations based on displacement factors are insufficient and risk misjudging of the climate benefit of wood products replacing non-wood alternatives. Demand-driven climate assessments on the wood product end-use level provide a safeguard against overestimating possible substitution effects (in contrast to supply-driven assessments) and indicate a more realistic impact on the forest system. The discussion of substitution or GHG reduction potentials should focus first on the question of which societal needs or functions (e.g. housing) can expect which demand projections and, secondly, on which alternative materials can be used to meet the functions, while emitting the least amount of GHGs possible compared to the defined reference (i.e., the status quo).

Forest management

Extending rotation lengths and decreasing harvest intensity in Sweden can induce considerable short-term climate change mitigation, regardless of the degree of (forgone) substitution effects. Shortening rotation lengths or increasing the harvest intensity in Swedish forest management leads to a slight additional climate warming effect. Leakage effects may compromise these outcomes.

Extending rotations in Swedish forests leads to higher substitution effects from sawlog-based HWPs and reduced substitution effects from pulpwood-based HWPs, while the opposite is given for shortening rotations.

The possibility of climate change mitigation following extended rotations or reduced harvests in Sweden is based on previous decades of active forest management in the country, which has resulted in a generally young forest state today.

Multi-family housing construction

Timber frame use instead of concrete frame in projected multi-family housing construction in Sweden would induce a slight climate benefit, unless the timber dwelling size increases and cross-laminated timber is the frame material.

The greatest climate benefit and smallest impact in Swedish forests is achieved when maintaining the currently dominant timber light frame construction type in Sweden and decreasing future dwelling sizes: less is more.

The additional sawlog harvest needed for nationally replacing concrete frame in MFHC with timber frame is only about 1% of the annual Swedish sawlog harvest.

Paper recycling

Increased paper recycling in Sweden can yield slight climate change mitigation given perfect substitution between primary pulp and recovered pulp.

The use of improved Swedish paper recycling for conserving Swedish forests yields slightly larger climate change mitigation than producing dissolving pulp for man-made cellulosic fiber to substitute cotton fiber. Additional substitution effects from the by-products of dissolving pulp making do not compromise this outcome.

Saving additional production of man-made cellulosic fiber avoids the risk of merely complementing markets without realizing actual substitution and climate change mitigation.

8. Future research

In order to further the understanding of climate change mitigation possibilities in the forest-based sector, future research should expand on the following:

More life cycle assessments from a system perspective on the product scale are required. These enhance knowledge as to the life cycle inventory and emission data of wood products, especially concerning emerging products still under development, such as lignin-based products. This can be done, for example, by applying prospective life cycle assessment and considering possible future emission scenarios based on shared socioeconomic pathways.

Market interactions should be considered in climate impact assessments of forest-based systems. This includes the projected demand and, for example, the consideration of price and cross-price elasticities of wood and non-wood products fulfilling the same function. Through this, more relevant knowledge on substitution effects can be obtained.

Impacts from climate change on forests should be increasingly included in mitigation assessments. Forest models require improved representation and simulation of future forest calamities and benefits, which would enhance the reliability of climate change mitigation outcomes.

Substitution effect communication of wood use should be based on demand-driven assessments. Estimates from supply-driven assessments produce too much uncertainty and, if based on displacement factors, do not align with official greenhouse gas reporting to the United Nations

Framework Convention on Climate Change for effective decision-making. Demand accounting and econometric analysis at the finished wood product end-use level is required for improved substitution effect communication.

Demand-driven market scale climate impact assessments from a system perspective are needed. This requires the generation of sufficient life cycle inventory data to cover all wood end uses fulfilling the needs or functions demanded by society and the consideration of international market dynamics, including trade.

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Popular science summary

Forests and wood products contribute to climate change mitigation. Assessing this potential requires a system perspective. In a system perspective, the total climate impact consists of four different components: the forest's uptake of carbon from the atmosphere, the carbon stored in wood products, fossil emissions from the forest sector, and the effects of substitution. Substitution occurs when wood products replace products with higher emissions. The sum of the four components determines the magnitude of the climate impact. A change in the systems often affects several components and in different directions, producing feedback effects. For example, if we study the effects of increased logging, there is a gain in carbon in wood products and substitution effects increase, but more fossil emissions are emitted in the forest-based sector and the carbon in the forest decreases.

This thesis aims to improve the understanding of the climate impacts of forests and wood products from a system perspective to support the design of effective climate change mitigation strategies. This was carried out in four case studies at two different scales (single wood product vs. multiple wood products) and with two different assessment methods (supply-driven and demand-driven).

The results of this thesis show that if only a single wood-based product is considered, for example a beverage carton, and analyzed in a supply-driven system perspective, the substitution effect of replacing a plastic bottle dominate the climate impact, and the use of the beverage carton therefore leads to climate benefits. However, if we analyze several wood-based products (a product portfolio), linked to changes in forestry practices from a supply-driven system perspective, then forests’ uptake of carbon plays a more important role and less intensive forest use contributes to climate benefits. If a single wood-based product such as structural timber is analyzed from a demand-driven system perspective, given that wooden frame replace concrete frame in newly built Swedish apartment buildings, this leads to little climate benefits compared to the effect of less intensive forest use. However, this only applies if the future apartments do not have a larger living area than the current ones. Finally, if increased paper recycling in Sweden were to be used to reduce pressure on national forests, this would also provide a small climate benefit compared to the effect of less intensive forest use.

Overall, these results show that the estimated climate change mitigation potential of forests and wood products depends on how the analysis is conducted. Does it focus on a single wood product or a whole product portfolio? Does it take into account how much of the wood product(s) is in demand? And what type of forest or substitute products are assumed?

General conclusions from the work are also that from a system perspective, the impact of forest carbon stocks plays the most important role in mitigating climate change and that the substitution effect risks being misjudged if the assessment is driven solely by supply (production). A demand-driven assessment instead ensures a more realistic estimate of the substitution effect.

To estimate the climate change mitigation potential of forests and wood products in future studies, the following steps are suggested: First, we should answer the question of which societal functions, e.g. housing, are to be met and what demand can be expected in the coming years. Secondly, we should explore the role that wood can play in fulfilling these functions instead of continuing to use other alternative products and materials. Thirdly, we calculate a possible substitution effect to estimate the climate benefits of replacing the alternative products and materials with wood products. And, finally, we assess the impact on the forest carbon balance.

Populärvetenskaplig sammanfattning

Skogar och träprodukter bidrar till att minska klimatförändringarna. För att kunna bedöma denna potential krävs ett systemperspektiv. I ett systemperspektiv utgörs den totala klimatbelastningen av fyra olika komponenter: skogens upptag av kol från atmosfären, kolet lagrat i träprodukterna, fossila emissioner från skogssektor, samt effekterna av substitution. Substitutionen uppstår när träprodukter ersätter produkter med högre utsläpp. Summan av de fyra komponenterna bestämmer klimatbelastningens storlek. En förändring i systemen påverkar ofta flera komponenter och i olika riktning som ger återkopplingseffekter. Studerar vi exempelvis effekterna av en ökad avverkning så ökar fossila emissioner från skogssektorn, kol i träprodukterna och substitutionen, men kolet i skogen minskar.

Denna avhandling syftar till att förbättra förståelsen av klimatpåverkan från skog och träprodukter ur ett systemperspektiv för att stödja utformningen av effektiva strategier för att motverka klimatförändringarna. Detta genomfördes i fyra fallstudier i två olika skalor (en enda träprodukt jämfört med flera träprodukter) och med två olika bedömningsmetoder (drivet av utbud respektive efterfrågan).

Resultaten från denna avhandling visar att om endast en enda träprodukt beaktas, till exempel en dryckeskartong, och analyseras i ett utbudsdrivet systemperspektiv kommer substitutionseffekten av att ersätta en plastflaska att dominera klimatpåverkan, och användningen av träprodukten leder därför till klimatnytta. Om vi däremot analyserar flera träprodukter (en produktportfölj), kopplat till förändrade skogsbruksmetoder ur ett utbudsdrivet systemperspektiv, då spelar skogens kolförråd en viktigare roll och en mindre intensiv skogsanvändning bidrar här till klimatfördelar. Om en enskild produktkategori som konstruktionsvirke analyseras ur ett efterfrågedrivet systemperspektiv, givet att trästommar ersätter betongstommar i nybyggda svenska flerfamiljshus, leder detta till liten klimatnytta jämförd med effekten från mindre intensiv skogsanvändning. Detta gäller dock endast om de framtida lägenheterna inte får större boarea än de nuvarande. Slutligen, om ökad pappersåtervinning i Sverige skulle användas för att minska trycket på de nationella skogarna, skulle detta också ge en liten klimatnytta.

Sammantaget visar dessa resultat att skogens och träprodukternas uppskattade potential att minska klimatförändringarna beror på hur analysen genomförs. Handlar den om en enskild träprodukt eller en hel produktportfölj? Tas hänsyn till hur mycket av träprodukten/träprodukterna som efterfrågas? Och vilken typ av skogs- eller ersättningsprodukter antas?

Generella slutsatser från arbetet är även att ur ett systemperspektiv spelar påverkan av kolförrådet i skogen den viktigaste rollen för att minska klimatförändringarna och att substitutionseffekten riskerar att missbedömas om bedömningen enbart drivs av utbudet (produktionen). En efterfrågedriven bedömning säkerställer istället en mer realistisk uppskattning av substitutionseffekten.

För att uppskatta skogens och träprodukternas potential att minska klimatförändringarna i framtida studier föreslås följande steg: Först bör vi besvara frågan om vilka samhällsfunktioner, t.ex. bostäder, som ska uppfyllas och vilken efterfrågan som kan förväntas under de kommande åren. För det andra bör det undersökas vilken roll trä kan spela för att uppfylla dessa funktioner i stället för att fortsätta använda andra alternativa produkter och material. För det tredje kan en eventuell substitutionseffekt beräknas för att uppskatta klimatnyttan av att ersätta de alternativa produkterna och materialen med träprodukter. Slutligen bedöms effekten på skogens kolbalans.

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Maximilian Schulte

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ORIGINAL RESEARCH

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access WILEY

Time dynamic climate impacts of a eucalyptus pulp product: Life cycle assessment including biogenic carbon and substitution effects

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Abstract

The forest sector can play a pivotal role in mitigating climate warming by decreasing emissions to the atmosphere and increasing carbon removals. In an expanding bioeconomy, the pulp and paper industry provides opportunities for various low-carbon wood products with promising substitution effects. However, assessing climate effects of wood product systems is complex and requires a holistic approach. The objective of this study was to advance time dynamic climate impact assessment of a bioeconomically promising wood product from a system perspective. For this purpose, a time dynamic life cycle assessment was conducted on a pulp-based beverage carton. The assessment included fossil value chain emissions from cradle to grave, effects from biogenic carbon in a eucalyptus plantation, and credits from substitution. A polyethylene terephthalate (PET) bottle was considered for material substitution (MS) and differing marginal electricity and heat mixes for energy substitution. The results revealed dominating climate warming from value chain emissions and slight offsetting by biogenic carbon from standing biomass and soil organic carbon, and short-term carbon storage in the beverage carton. MS and displacing marginal energy mixes transformed the climate warming into a substantial total cooling effect. However, substitution effects varied strongly in terms of substitution factors and temperature change with varying replacement rate of the beverage carton and different marginal energy mixes. A climate cooling range of $-0.8 \cdot 10^{-15}$ to $-1.8 \cdot 10^{-15}$ K per unit of beverage carton by 2050 was found, highlighting potential relevance for climate policy making. Thus, production and use of wood-based beverage cartons over PET bottles can have climate cooling effects. Further assessments on alternative forestry systems (e.g., Nordic forests) are needed to identify the role of biogenic carbon in holistic climate assessments, with dynamic substitution effects included to increase the validity.

KEYWORDS
beverage carton, biogenic carbon, climate impact, LCA, pulp, substitution effect, temperature change, time dynamic, wood product

1 | INTRODUCTION

The urgently needed mitigation of global greenhouse gas (GHG) emissions requires efforts to reduce emissions to the atmosphere and increase carbon removals (IPCC, 2014). In efforts to limit climate warming below 1.5°C (UNFCCC, 2015), harvested wood products (HWPs) from the forest sector can play a pivotal role within the framework of climate-smart forestry (Nabuurs et al., 2018).

Forests sequester carbon dioxide (CO_2) through photosynthesis and store it as biogenic carbon in biomass and soil organic carbon (SOC). This biogenic carbon from biomass is retained in HWPs, capturing CO_2 from the atmosphere. In addition, production of HWPs generally releases less GHG emissions than processing functionally equivalent non-wood products, especially when the wood is sourced from sustainable forestry (Geng et al., 2017). Thus, wood products can have substitution effects through avoided GHG emissions by displacing non-wood materials (Leskinen et al., 2018).

The European Union (EU) strives for climate neutrality by 2050 (EC, 2020a) and acknowledges the climate mitigation role of the forest sector and HWPs in its bioeconomy strategy, where abating climate change is linked to "[...] a renewed bio-based industrial base reducing energy demand and lowering emissions" (EC, 2018). In this context, "[one] pioneer in making the EU low-carbon bioeconomy an industrial reality" is stated to be the pulp and paper industry (EC, 2020b). In addition, the raw material pulpwood can be the source of a variety of new HWPs with promising market potential in an expanding bioeconomy (Hurmekoski et al., 2018).

However, European demand for pulp is increasingly being met by imports from South American eucalyptus pulpwood production (FAO, 2019; González-Goméz, 2019; Judl et al., 2011), which supplied 72% of the EU's pulp imports in 2011 (Indufor, 2013). This trend can bear the danger of increased GHG emissions, for example, due to related land use change (LUC), if native forest is converted to eucalyptus plantations (Bernstad Saraiva et al., 2017). Consequently, a shift in emissions, that is, "leakage effects" could occur, contravening the EU's ambition for reducing energy demand and GHG emissions in a bioeconomy (Harmon, 2019; Leskinen et al., 2018). Due to their large volumes, pulp products in form of packaging, textile (e.g., viscose), or chemical applications are considered to have a substantial GHG mitigation effect, via displacement of emission-intensive materials, such as plastic packaging, or synthetic fiber used for clothing (Leskinen et al., 2018). However, information about actual GHG substitution effects is lacking, especially for packaging products such as pulp, because of the great variety of alternative materials (Leskinen et al., 2018).

One pulp product with large production outputs and a potentially promising substitution effect is the beverage carton. In a meta-study of 20 life cycle assessments (LCAs), Falkenstein et al. (2010) found that the beverage carton was usually attributed the lowest climate impact among functionally equivalent products such as glass or polyethylene terephthalate (PET) bottles. This has been confirmed by a later review on beverage cartons by O'Sullivan et al. (2016) and a comparative LCA on beverage carton usage set in Northern Europe (Markwardt et al., 2017).

Life cycle assessment (ISO, 2006a, 2006b) is an established methodology for analyzing climate effects of wood utilization. As reviewed by Markwardt et al. (2017) and Falkenstein et al. (2010), various LCAs have investigated the climate effects of the forest sector (Klein et al., 2015), wood utilization for energy (Wolf et al., 2016), material application (Sahoo et al., 2019) or Eucalyptus cultivation in form of a time-dependent approach (Porsö et al., 2016). However, these LCAs often leave a research gap by omitting either system-holistic or time dynamic climate impact assessment, for which the term "system perspective" is used in the following. Filling this research gap is essential to understand the wider implications of HWP use in policy making on the climate (Suter et al., 2017).

A system perspective can integrate five major aspects, by: (i) including climate effects of biogenic carbon which are still mostly considered neutral (Røyne et al., 2016), that is, carbon sequestration via photosynthesis equals the eventual carbon emission along the life cycle (Head et al., 2019); (ii) accounting for substitution (energy substitution [ES], material substitution [MS]) effects of the wood use (Garcia et al., 2020), which is associated with great uncertainties, especially for emerging HWPs (Leskinen et al., 2018); (iii) cascading use of wood, which occurs when "wood is processed into a product and this product is used at least once more either for material or energy purpose" (EC, 2016a), making cascading a potential means to improve the climate performance of a HWP system

(Thonemann & Schumann, 2018); (iv) including sufficient sensitivity analysis for the HWP system assessed, for example, in terms of changing substituted future marginal energy mixes (Hammar & Levihn, 2020); and (v) applying climate metrics appropriate for accounting for time dynamic effects of GHG emissions and sequestrations (Helin et al., 2013; Levasseur et al., 2010), to compensate for the shortcomings of commonly used static climate metrics such as global warming potential (GWP) in terms of time-dependent accounting (Breton et al., 2018). Examples of such metrics are the $\mathrm{GWP}_{\mathrm{bio}}$ (Cherubini et al., 2011), the time-dependent radiative forcing (RF) (Sathre & Gustavsson, 2012), or the absolute global temperature change potential (AGTP) (Myhre et al., 2013).

The intention of the present study was to apply a system perspective in assessment of the climate effects of wood material application, closing the existing research gap. A system perspective was applied in a case study of a UHT milk beverage carton (hereafter "beverage carton") on the Northern European market produced from South American eucalyptus pulpwood. Therewith, the objective of the study was to conduct a time dynamic climate impact assessment of a bioeconomically promising HWP including biogenic carbon stocks and fluxes, and substitution effects from energy and material displacement, to advance the understanding of climate effects from wood product systems.

2 | MATERIALS AND METHODS

2.1 | Scope

The system boundary of the beverage carton life cycle assessed in this study contained the following three components:

Biogenic carbon stocks and fluxes, including standing aboveground and belowground biomass, and also SOC and carbon storage in the HWP (pulpwood, pulp, beverage carton). A theoretical landscape perspective was modeled (Cintas et al., 2016; Eliasson et al., 2013) for the eucalyptus plantation and grassland was considered as a land-use reference system (Koponen et al., 2018) to account for potential climate impact mitigation from replacing a non-plantation benchmark (Peñaloza et al., 2019).

Fossil value chain emissions of the beverage carton, which were accounted for from cradle to grave and geographically divided into two parts: Uruguay, where emissions from the eucalyptus plantation and pulpwood processing were assumed to occur, and Sweden, where emissions from finishing pulp to beverage carton and the end-of-life stage (incineration) were set. In between both parts, emissions from shipping were included.

Substitution effects of material and energy displacement. A full-barrier PET bottle, including its life cycle from cradle to grave and its potential ES, was considered, since plastic products have the second greatest market share among food packaging materials, after paper and board (Muncke, 2020). Recycling of the PET bottle and a corresponding replacement rate (R) was also accounted for, based on Hammar et al. (2020). ES was matched to the geographical region where the energy was generated, that is, electricity produced from the Uruguayan pulp mill substituted marginal Uruguayan electricity mixes, while energy produced from waste incineration in Sweden displaced marginal Swedish energy mixes. Thus, cascading use was considered by using the materials at the end of life for energy recovery. No use phase was accounted for, because it was assumed that differences in usage, and thus differences in emissions, were negligible.

A dynamic life cycle inventory including annual inputs and outputs was applied for all flows and processes since it improves accuracy of life cycle impact results and thus the entire LCA outcome (Lueddeckens et al., 2020). Two functional units and time horizons were set. The first functional unit covered a time horizon of 100 years of beverage carton production and was based on one hectare of eucalyptus plantation, to enable comparisons with the climate metric GWP_{100} and thus other studies. The second functional unit covered a time horizon of 50 years of beverage carton production and was based on one unit of beverage carton. This was to highlight potential relevance for climate policy making. Climate impact allocation between the products and by-products was avoided, and system expansion including biogenic carbon and substitution effects was applied. On the plantation, harvest residues (leaves, branches, stump, roots, bark) were assumed to be left in the field, and thus to act as input to SOC. The multi-output process in the pulp mill resulted in the product, pulp, and various by-products. The burdens from these by-products were included in form of ES via exported electricity replacing marginal mixes in Uruguay.

Sensitivity analyses were carried out to test the effect of assumptions regarding the substitution effects, one on differing material replacement rates and one on changing the displaced marginal energy mixes considering the functional unit of one beverage carton.

2.2 | Biogenic carbon

Biogenic carbon stocks and fluxes occurred along the entire life cycle (Figure 1). The biogenic carbon from standing biomass and SOC was calculated from a theoretical landscape perspective (Cintas et al., 2016; Eliasson et al., 2013). In the plantations, all standing aboveground

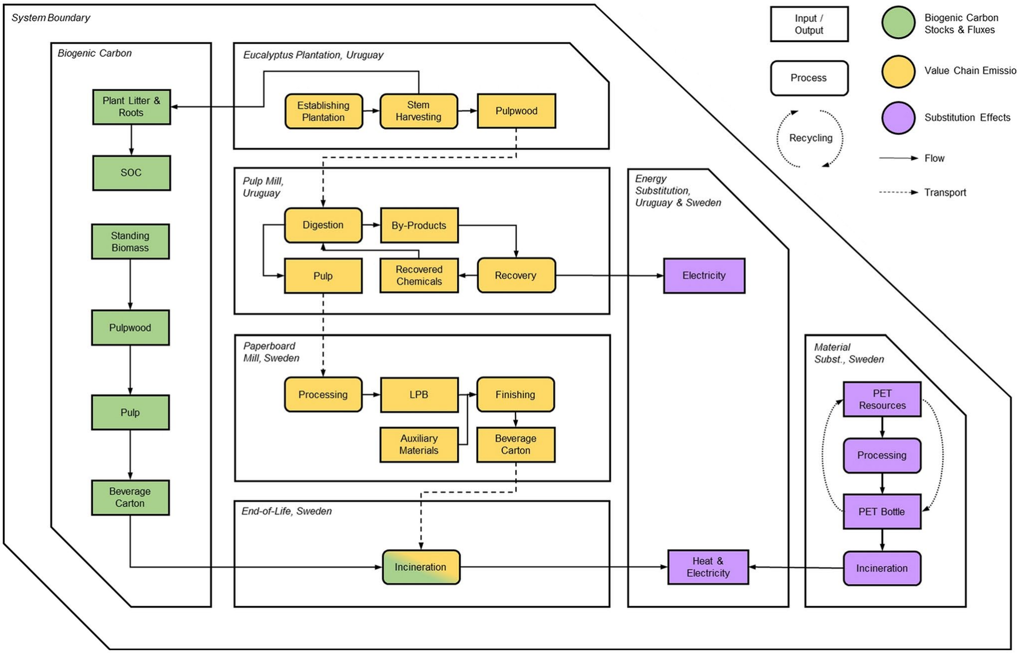


FIGURE 1 System boundary of beverage carton sourced from South American eucalyptus pulp, encompassing biogenic carbon stocks and fluxes, value chain emissions, and substitution effects. LPB, liquid packaging board; PET, polyethylene terephthalate; SOC, soil organic carbon

biomass except for the harvested stems was assumed to be left on the ground to decompose and to function as input to SOC. The resulting annual SOC fluxes were calculated using the dynamic soil carbon model Yasso 15 (Hammar et al., 2020; Järvenpää et al., 2018). An SOC value of 44.7 Mg C ha^{-1} for the former land use category grassland was applied, based on FAO and CMCC (2017), and acted as the reference case. The rotation period of each plantation was set to 9 years and average harvest yield to 76.8 Mg pulpwood ha^{-1}, with a biogenic carbon content of 38.4 Mg ha^{-1} and assuming a moisture content of 50% (Giraldo & Hyman, 1996). Biogenic carbon storage and decay within the HWPs (pulp and beverage carton) were modeled based on Rüter et al. (2019), considering a half-life of 1.9 years.

2.3 | Value chain emissions

2.3.1 | Eucalyptus plantation

Value chain emissions included operations on the eucalyptus plantation (Figure 1), and were modeled according to Gabrielle et al. (2013), with modifications, and based on site-specific data for a Uruguayan cultivation system. Field operations occurred at two different points in time in the rotation. In the first year, they included soil preparation in the form of plowing, mechanical planting of seedlings, fertilizer production, and fertilizer application. In the last year of the rotation cycle, harvesting was performed with a one-grip harvester, followed by ditch cleaning and, finally, field transport of the pulpwood logs to the road. All processes were assumed to be fueled by diesel, with emissions from diesel production and consumption based on Giuntoli et al. (2015). Fertilizer application was set to 110 kg N ha^{-1}, 33 kg P ha^{-1}, and 96 kg K ha^{-1} per rotation period, adapted from Timander (2011). For all fertilizers and forms of biomass litter, direct and indirect N_2O emissions due to, for example, nitrate leaching were included, based on IPCC (2019).

Subsequent lorry transportation (and associated emissions) was assumed to be with a EURO 5 truck. Average transportation distance was set at 180 km from the plantation to the pulp mill, based on site-specific location information. Capacity of the truck (45 Mg) was based on Simons (2019) and tare weight (20.5 Mg) was based on Trzciński et al. (2018). Emissions from diesel use were calculated based on Giuntoli et al. (2015).

2.3.2 | Pulp mill

Eucalyptus pulpwood was assumed to be processed into chemical pulp within modern pulp mill facilities (Figure 1). Like the majority of pulp making today, chemical pulping via the sulfate (or Kraft) process is the dominant practice in Uruguay (Kuparinen et al., 2019). All processes occurring in the pulp mill were divided into two parts: the digestion (pulp making) process and the by-product recovery process including production of surplus energy (Kuparinen et al., 2019). Both processes were modeled based on Corcelli et al. (2018) and primary data from the mill operator, while background data on auxiliary materials and energy-related emissions were taken from the ecoinvent database (Wernet et al., 2016). All by-products from pulp making (components of "black liquor") were assumed to be used for energy recovery applying a LHV of 12 MJ kg^{-1} (ECN, 2021) as it is common practice in modern pulp mills in Uruguay (Kuparinen et al., 2019; Montes del Plata SA, 2021). This surplus energy was redirected to the national grid in form of electricity where it was considered to cause substitution of marginal mixes, whose modeling was based on Hagberg et al. (2017) and MIEM (2019; Supporting Information S1). For the recovery boiler, an efficiency of 67% was assumed, based on Zhao et al. (2019).

The pulp produced was assumed to be shipped to Sweden for finishing into liquid packaging board, which was used in the final product, the beverage carton. Transport distances were modeled based on data from NTMCalc 4.0 (NTM, 2020), while GHG emissions were based on the ecoinvent database 3.6 (Wernet et al., 2016), in accordance with McKinnon and Piecyk (2010) and NTMCalc 4.0 (NTM, 2020). Transport distance amounted to 12,600 km from the pulp mill in Uruguay to the port in Sweden. Transport emissions were modeled using a well-to-wheel approach, that is, emissions from infrastructure were neglected and only those from diesel combustion were included. In Sweden, the pulp was transported by lorry from the port to the packaging board mill, located 260 km away. This transport was modeled similar to the lorry transport within Uruguay.

2.3.3 | Paperboard mill

At the packaging board mill, pulp was processed into liquid packaging board, from which the beverage carton was created. Energy requirements and auxiliary materials (i.e., aluminum, low-density polyethylene [LDPE], polypropylene [PP]) were adapted from Corcelli et al. (2018) and based on first-hand data from the mill operator. Finishing liquid packaging board for the beverage carton required adding LDPE and aluminum for the coating, and PP for the cap. Emissions data on these additives were taken from the ecoinvent database 3.6 (Wernet et al., 2016). A final transport stage of 100 km to the end-of-life stage was assumed, based on the average national transport distance for Sweden (Eurostat, 2020). For this, similar conditions as in previous lorry transportation were applied.

2.3.4 | End of life

The end-of-life stage represented incineration under average Swedish conditions. Processes such as collecting, sorting, and storing were omitted as they were considered to be similar for both beverage carton and PET bottle. A combined heat and power plant with heat efficiency of 45% and electricity efficiency of 30% was assumed for combusting the beverage carton and PET bottle, based on EC (2011). The energy content of the products and emissions from incineration was calculated based on the relative share of the component materials. Emissions data were taken from the ecoinvent database 3.6 (Wernet et al., 2016). The lower heating value (LHV) was set to 18.23 MJ kg^{-1} for the beverage carton and 25.1 MJ kg^{-1} for the PET bottle. The energy content of the components in the products (Swedish Standard Institute, 2004) was set to 12.6 MJ kg^{-1} for liquid packaging board, 22.0 MJ kg^{-1} for PET, 44.0 MJ kg^{-1} PP for the caps, 43.0 MJ kg^{-1} LDPE for the labels or coatings, and 27.0 MJ kg^{-1} for carbon black, which was used as a pigment for the PET bottle. The LHV for aluminum was excluded, since it was assumed not to deliver energy from its combustion.

2.4 | Substitution effects

2.4.1 | Energy and material substitution

Material substitution of the PET bottle was modeled to be representative for a European setting and comprised (Doka, 2013; EFBW, 2020; Fröhlich, 2017): resource sourcing for PET production, the PET production process and PET bottle making, recycling, and disposal by incineration. Between each stage, similar lorry transportation conditions as for the beverage carton were assumed.

Substitution of energy within the system boundary comprised three parts: (i) surplus energy from the Uruguayan pulp mill, which replaced marginal electricity mixes, whose modeling was based on Hagberg et al. (2017) and MIEM (2019); (ii) released heat and electricity from incineration of the beverage carton, which substituted a marginal Nordic heat and electricity mix with composition modeled based on Hagberg et al. (2017);

and (iii) forgone heat and electricity replacement from avoided end-of-life incineration of the substituted PET bottle, also based on the marginal Nordic heat and electricity mix. In addition, a sensitivity analysis was performed using different Uruguayan marginal electricity mixes and Swedish marginal heat and electricity mixes for the years 2020, 2030, and 2040, modeled based on Hagberg et al. (2017) and MIEM (2019). Detailed information on these marginal energy mixes can be found in Supporting Information S1.

2.4.2 | Substitution factors

Substitution factors (SFs) for replacing the PET bottle with the beverage carton were calculated based on Sathre and O'Connor (2010):

$$\mathrm{SF} = \frac{\mathrm{GHG}_{\text{non - wood}} \cdot R - \mathrm{GHG}_{\text{wood}}}{\mathrm{WU}_{\text{wood}} - \mathrm{WU}_{\text{non - wood}} \cdot R}, \qquad (1)$$

where the SF is given in Mg $\mathrm{C}_{\text{fossil}}$ Mg^{-1} $\mathrm{C}_{\text{biogenic}}$; $\mathrm{GHG}_{\text{non-wood}}$ and $\mathrm{GHG}_{\text{wood}}$ denote the GHG emissions from production and incineration of the non-wood and wood product, respectively, expressed in mass units of carbon corresponding to the CO_2 equivalents (CO_2-eq) of the emissions; $\mathrm{WU}_{\text{wood}}$ and $\mathrm{WU}_{\text{non-wood}}$ represent the amount of wood used in the wood and non-wood product, respectively, also given in mass units of carbon; and R is replacement rate (R), based on Hammar et al. (2020).

The terms $\mathrm{GHG}_{\text{non-wood}} \cdot R$ and $\mathrm{WU}_{\text{non-wood}} \cdot R$ in Equation (1) account for recycling the PET bottle into another one that fulfills the same function (Figure 1). As the baseline case, the European PET bottle recycling rate of 52% (EUNOMIA, 2020) was applied, and thus, $R = 0.48$. A sensitivity analysis was performed by applying the Swedish PET bottle recycling rate of 83% (SCB, 2019; $R = 0.17$) and by assuming no recycling of the PET bottle, meaning that one beverage carton replaced one PET bottle ($R = 1$). Overall, recycling and associated emissions were only assumed for the PET bottle because recycling of PET bottles into the same product is legitimate and common practice. Recycling was not assumed for the beverage carton, as virgin pulp fiber is mainly used in production to guarantee inert and safe food packaging conditions in accordance with EC (2016b).

To account for the entire value chain, the SF of the MS effect was calculated as:

$$\mathrm{SF}_{\text{total}} = \mathrm{SF}_{\mathrm{P}} + \mathrm{SF}_{\text{EoL}}, \qquad (2)$$

where the total substitution factor $\mathrm{SF}_{\text{total}}$ is given in Mg $\mathrm{C}_{\text{fossil}}$ Mg^{-1} $\mathrm{C}_{\text{biogenic}}$, SF_{P} is the substitution factor from the material production stage, and SF_{EoL} is the substitution factor comprising emissions from the end-of-life stage and ES. It follows that the larger the $\mathrm{SF}_{\text{total}}$, the greater the assumed climate mitigation effect via replacement.

2.5 | Climate impact metrics

Climate effects can be calculated at different steps along the cause–effect chain from GHG emission to actual climate change and its consequences (Myhre et al., 2013). In this study, two different metrics, GWP and AGTP, were applied to assess the effect on the climate. GWP represents the cumulative RF of a GHG relative to the cumulative RF of CO_2 for a determined time frame (Joos et al., 2013). The time frame is often set for 100 years and the corresponding GWP_{100} is useful for comparisons with other studies. However, GWP does not consider the time dynamics of GHG emissions or accounts for varying points in time along the life cycle when GHG fluxes occur. Apart from CO_2, which stays airborne until it is partly taken up via plants or the oceans, the GWP_{100} includes methane (CH_4) and nitrous oxide (N_2O) emissions. For fossil CH_4, the GWP_{100} is 30-fold stronger than that of CO_2 (28-fold for biogenic carbon) with a perturbation lifetime of 12.4 years, while for N_2O, it is 265-fold stronger with a perturbation lifetime of 121 years (Myhre et al., 2013). In this study, no climate-carbon feedbacks were considered.

Absolute global temperature change potential, defined by Myhre et al. (2013), is synonymous with time dynamic temperature change or temperature change in this study. Compared with GWP, it is a climate metric one step further down the cause–effect chain from emissions to climate change and impacts. It therefore has greater policy relevance, but greater uncertainties are associated with its results. The AGTP value represents the response in global mean surface temperature at a given point in time induced by a change in RF due to a pulse emission of a GHG and is expressed in degrees Kelvin (K). The differing radiative efficiencies of the GHGs, which alter the balance of incoming, short-wave solar radiation, and outgoing, long-wave terrestrial radiation to varying degrees, and the differing perturbation lifetimes of the GHGs in the atmosphere are considered. In this study, AGTP was calculated based on GHG fluxes from CO_2, CH_4, and N_2O over a time horizon of 100 years and 50 years. The perturbation lifetime of CO_2 was modeled based on the Bern carbon cycle model (Joos et al., 2001, 2013), in which the molecule stays airborne until it is taken up by oceans or the biosphere. For CH_4 and N_2O, average perturbation lifetime was 12.4 and 121 years, respectively (Myhre et al., 2013). Indirect effects of ozone and water vapor on the radiative forcing of CH_4 were included in the climate model. The AGTP from each GHG considered is described by:

$$\mathrm{AGTP}_x(H) = \int_0^H \mathrm{RF}_x(t)\, R_T(H-t)\, dt, \tag{3}$$

where RF and the climate response function (R_T) form a convolution over the assessed time horizon (H) by a change in the RF from a pulse emission of a GHG x. Thus, AGTP accounts for the timing of GHG emissions and their perturbation lifetimes, enabling assessment of time-dependent climate effects.

3 | RESULTS

3.1 | Biogenic carbon dynamics of the eucalyptus plantation

Figure 2 shows the modeled time-dependent carbon stocks of the eucalyptus plantation from a stand perspective, divided into SOC, stems and bark, stumps, branches, leaves, and roots over two rotation cycles. The modeled biogenic carbon stocks of standing biomass accumulated throughout each rotation period, by annually decreasing incremental growth. Stems accounted for the largest share of biogenic carbon from standing biomass, followed by stumps, roots, branches, and leaves. At the start of each rotation, total biogenic carbon from standing biomass amounted to 11 Mg C ha^{-1}, while in the final year of the rotation cycle (year 9), it had increased to a total of 56 Mg C ha^{-1}. At the end of year 9, eucalyptus stems (excluding bark) were harvested, which amounted to 38 Mg C ha^{-1}, and the next rotation cycle began. Stocks of SOC showed an opposing pattern. During harvest years, stocks increased since fallen litter (e.g., leaves & roots) and harvest residues (bark and stumps) were added to the soil. Thereafter, the SOC stock decreased slightly from year to year until the rotation cycle reached the next harvest.

3.2 | Global warming potential

Figure 3 shows the GWP_{100} per unit of beverage carton from a landscape perspective. In total, one beverage carton amounted to 66.0 g CO_2-eq per package when excluding substitution (Figure 3a). Value chain emissions and incineration clearly dominated the climate impact, with most GHGs emitted by operations and energy requirements within the Uruguayan pulp mill (25%) and the Swedish packaging board mill (44%), and by combustion of LDPE and PP from the beverage carton (29%). By contrast, value chain emissions from the plantation and transport were minor. Moreover, biogenic carbon from standing biomass, HWPs, and SOC was marginal in the overall CO_2-eq balance of the beverage carton and barely offset the emissions. In total, the sequestration effect from biogenic carbon amounted to −2.0 g CO_2-eq per unit of beverage carton. When substitution effects were included in the GWP_{100} (Figure 3b), one beverage carton amounted to −83.7 g CO_2-eq. When forgone substitution credits from avoided PET bottle combustion and emissions of beverage carton incineration were subtracted from the ES credit, the offset still showed a moderate CO_2-eq saving. In addition, MS contributed substantially to offsetting fossil value chain

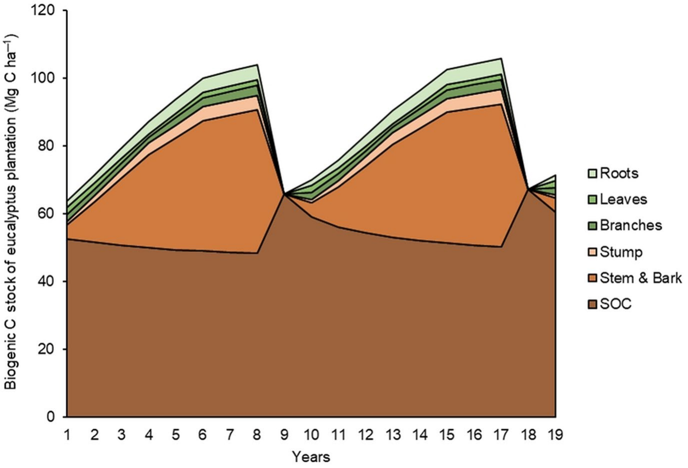


FIGURE 2 Stand perspective of the biogenic carbon stocks during the first two 9-year rotation periods in the modeled eucalyptus plantation. *Note*: Values represent state at the end of the year. SOC, soil organic carbon

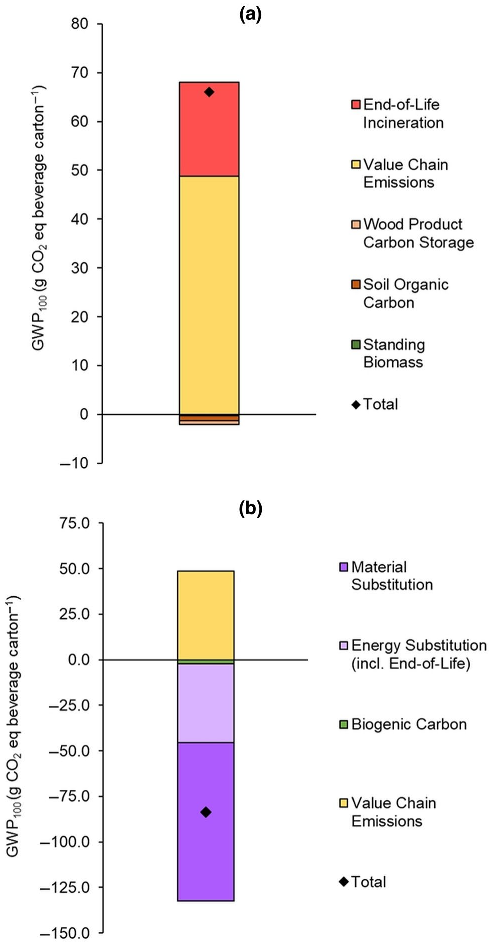


FIGURE 3 (a) GWP_{100} of a beverage carton excluding substitution effects, including value chain emissions, end-of-life emissions from incineration, and biogenic carbon fluxes from different sources. (b) GWP_{100} of a beverage carton including substitution effects, value chain emissions, and biogenic carbon fluxes. Substitution effects assume moderate PET bottle replacement ($R = 0.48$) and a fossil-intense marginal Uruguayan electricity and Swedish energy mix displacement (mix in 2020), according to Hagberg et al. (2017) and adapted from MIEM (2019). *Note*: End-of-life emissions from beverage carton incineration are included in energy substitution, which also considers forgone energy credits from avoided PET combustion. Figures show the results from a landscape perspective. GWP, global warming potential; PET, polyethylene terephthalate

emissions. Biogenic carbon effects continued to make only a minor contribution to total GWP_{100}.

TABLE 1 Substitution factors (SFs) for varying replacement rate (R) of a beverage carton sourced from South American eucalyptus pulpwood and produced and disposed of in Sweden. Total substitution factor ($\mathrm{SF}_{\mathrm{total}}$) is divided into the substitution factors caused by production (SF_{P}) and by the end-of-life stage including energy recovery ($\mathrm{SF}_{\mathrm{EoL}}$). Negative values indicate fossil carbon savings

	Substitution Factor (g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$)		
Replacement rate (R)	**SF_{P}**	**$\mathrm{SF}_{\mathrm{EoL}}$**	**$\mathrm{SF}_{\mathrm{total}}$**
0.48	−0.1	−2.1	−2.2
1	−1.2	−1.2	−2.4
0.17	0.6	−2.7	−2.1

3.3 | Substitution factors including replacement rates

The total substitution factors ($\mathrm{SF}_{\mathrm{total}}$) of the beverage carton are presented in Table 1, where negative values indicate net fossil carbon removal. Moreover, the sensitivity of the SFs to varying replacement rates (R) of the PET bottle is shown. The baseline case, a moderate replacement rate ($R = 0.48$), resulted in a total substitution factor of −2.2 g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$. This saving was almost entirely composed of $\mathrm{SF}_{\mathrm{EoL}}$, while SF_{P} made a minor contribution. The highest $\mathrm{SF}_{\mathrm{total}}$ was found for one beverage carton replacing one PET bottle ($R = 1$) and amounted to −2.4 g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$. The lowest $\mathrm{SF}_{\mathrm{total}}$, −2.1 g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$, was obtained with low replacement ($R = 0.17$). In this case, SF_{P} was positive, 0.6 g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$, but was outweighed by $\mathrm{SF}_{\mathrm{EoL}}$ equaling −2.7 g $\mathrm{C}_{\mathrm{fossil}}$ g^{-1} $\mathrm{C}_{\mathrm{biogenic}}$.

3.4 | Time dynamic temperature change

3.4.1 | Temperature change from biogenic carbon fluxes

Biogenic carbon fluxes decreased the atmospheric concentration of CO_2 in a landscape perspective over a time horizon of 100 years. This induced a negative temperature change, that is, climate cooling (Figure 4). The effect was the strongest during the first 30 years and leveled off in subsequent decades. In total, the climate cooling effect from SOC was five- to six-fold stronger than the effect from biogenic carbon in standing biomass. Moreover, temperature change caused by biogenic carbon fluxes from HWPs initially followed a similar trend as SOC, while later it had a moderately weaker cooling effect.

FIGURE 4 Temperature change from biogenic carbon fluxes of the modeled eucalyptus plantation's standing biomass, soil organic carbon, and harvested wood products, given per ha from a landscape perspective

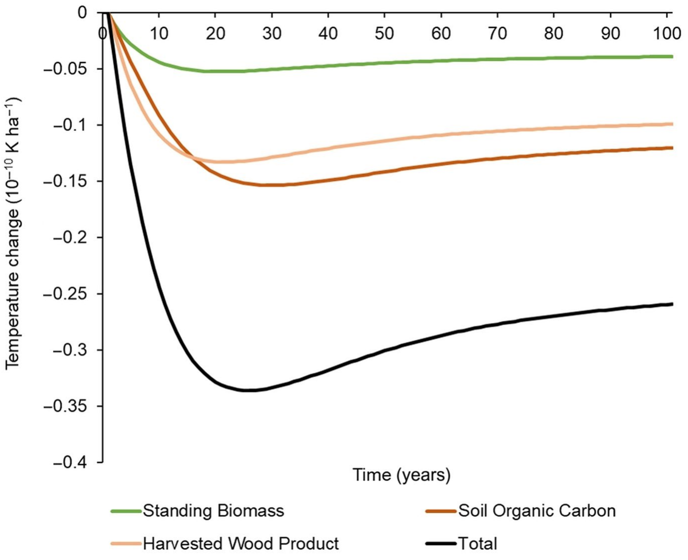
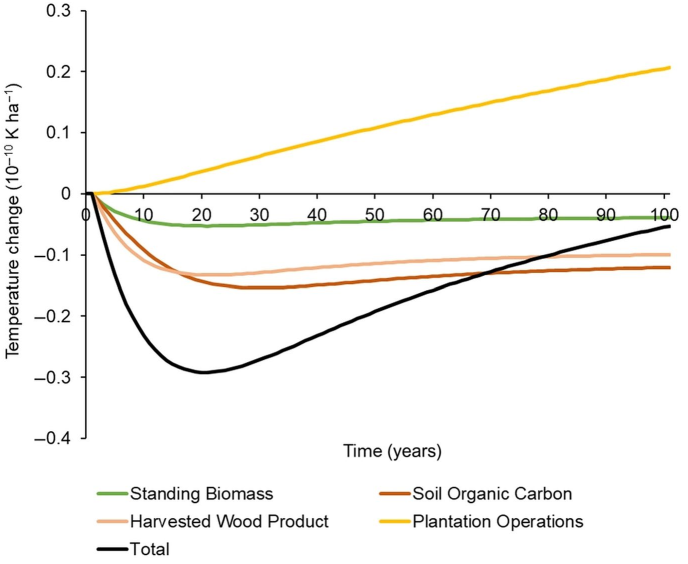


FIGURE 5 Temperature change from all forms of biogenic carbon fluxes and fossil emissions from operations on the plantation, given per ha from a landscape perspective



3.4.2 | Temperature change from biogenic carbon and value chain emissions

Figure 5 illustrates the temperature change from plantation operations and biogenic carbon per ha over a time horizon of 100 years. Irrespective of the continuous climate warming from the fossil emissions of the operations, the sum of biogenic carbon fluxes clearly outweighed this effect and transformed the total into climate cooling. This climate cooling was strongest in the first three decades and was then steadily offset by fossil emissions, but without becoming overall climate warming over the time horizon assessed.

Figure 6 shows the temperature change per unit of beverage carton over a time horizon of 50 years including emissions from the entire value chain, end-of-life incineration, and biogenic carbon. In general, the trend was similar to that obtained for GWP_{100} (see Figure 3a). The

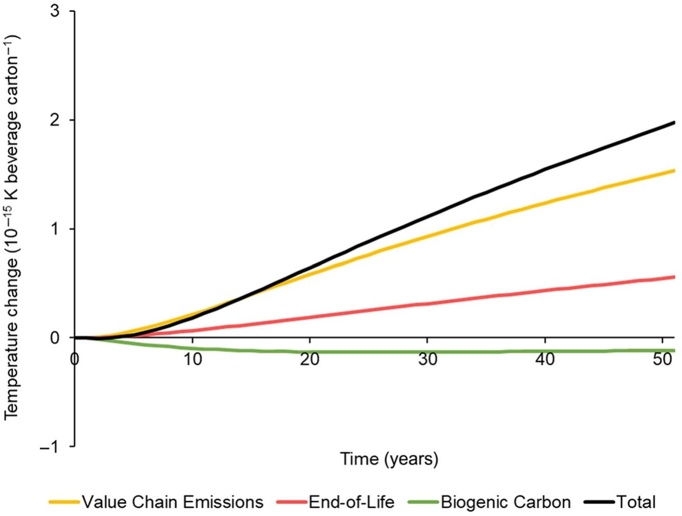


FIGURE 6 Temperature change from value chain emissions, end-of-life incineration, and all biogenic carbon fluxes, given per unit of beverage carton from a landscape perspective

climate cooling effect from biogenic carbon fluxes was negligible compared with the climate warming from fossil emissions from the value chain and end of life. However, in contrast to GWP_{100}, the temperature change showed steadily increasing climate warming over time. In the very first years of the time horizon assessed, climate warming was outweighed by the climate cooling from biogenic carbon fluxes. Overall, end-of-life emissions contributed around one-third, and residual value chain emissions two-thirds, to the total temperature change.

3.4.3 | Temperature change from a system perspective

The system perspective of one unit of beverage carton temperature change (Figure 7) included biogenic carbon, fossil value chain emissions, and energy and MS over a time horizon of 50 years. It showed a similar trend to GWP_{100} (see Figure 3b). From the start, climate cooling from energy and MS strongly offset climate warming from value chain emissions. Simultaneously, biogenic carbon fluxes only slightly influenced the overall climate effect. In total, a climate cooling effect was induced and continued to increase over time, mainly influenced by fossil value chain emissions and MS effects.

3.4.4 | Sensitivity analysis

Figures 8 and 9 present the results of sensitivity analyses for the product system of the beverage carton. Both consider a time horizon of 50 years from 2020 until 2070 and include the EU's climate neutrality target for 2050.

Figure 8 shows temperature changes of different MS, that is, three different replacement rates (R) of the beverage carton and its effects on the entire product system (Total), which is defined as in Figure 7. Irrespective of replacement rate considered, the climate cooling of the entire product system constantly increased over time. However, the magnitude of the cooling effect differed substantially depending on the replacement rate. Strong climate cooling was obtained with a high replacement rate ($R = 1$), whereas low replacement rate ($R = 0.17$) resulted in minor climate cooling over time. By 2050, a total temperature change of approximately $-1.8 \cdot 10^{-15}$ K beverage carton^{-1} was obtained for high replacement ($R = 1$), and $-1.3 \cdot 10^{-15}$ K beverage carton^{-1} for low replacement ($R = 0.17$). Thus, a temperature change difference of approximately $0.5 \cdot 10^{-15}$ K was obtained for the year 2050 by changing replacement rates per unit of beverage carton.

Figure 9 presents the temperature change of the entire product system (Total) for three different cases of ES based on marginal Uruguayan electricity and Swedish energy mixes. The climate cooling effect from ES clearly decreased from a fossil-intense mix (marginal mix for 2020) to a moderately fossil-based mix (marginal mix for 2030). The climate cooling effect became minor when a low fossil-based, that is, renewable-intense ES mix (marginal mix for 2040) was considered. From a system perspective, this meant that fossil-intense ES led to a contribution of approximately $-1.5 \cdot 10^{-15}$ K beverage carton^{-1} to the EU's climate neutrality target for the year 2050. In contrast,

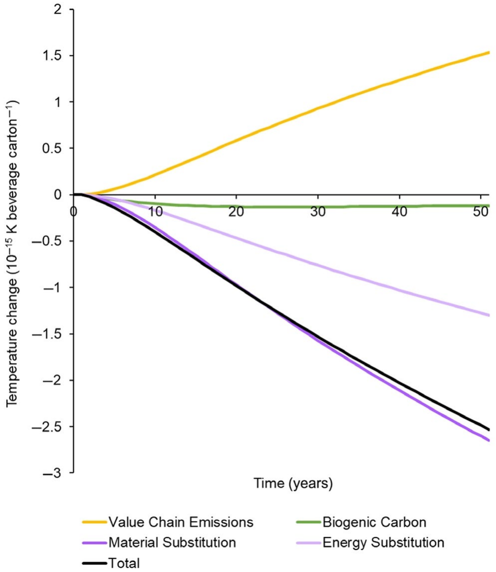


FIGURE 7 Temperature change per unit of beverage carton from a system perspective, including fossil value chain emissions, biogenic carbon fluxes, and substitution. Substitution effects assume a moderate PET bottle replacement rate ($R = 0.48$) and a fossil-intense marginal Uruguayan electricity and Swedish energy mix displacement (mix in 2020), according to Hagberg et al. (2017) and adapted from MIEM (2019). *Note*: End-of-life emissions from beverage carton incineration are included in energy substitution, which also considers forgone energy credits from avoided PET combustion. The results are shown from a landscape perspective. PET, polyethylene terephthalate

renewable-intense ES induced a temperature change of around $-0.7 \cdot 10^{-15}$ K beverage carton^{-1}. Thus, differences in ES, based on differing marginal energy mixes, induced a temperature change difference of about $0.8 \cdot 10^{-15}$ K beverage carton^{-1} by 2050.

Overall, the temperature change range caused by altered replacement rate of the beverage carton (Figure 8) was substantially larger than of changing substituted marginal energy mix (Figure 9).

4 | DISCUSSION

4.1 | Time dynamic climate effects including biogenic carbon and substitution

The climate assessment in the present study expanded on previous LCAs on wood products by including fossil value chain emissions with biogenic fluxes (Røyne et al., 2016) and substitution effects, assessed in a time dynamic approach (Breton et al., 2018). The study also provided new information on substitution factors, since pulp and paper or chemicals are often omitted in LCA studies, as stated by Soimakallio et al. (2016), and geographical regions such as South America are rarely considered, as mentioned by Leskinen et al. (2018). The climate effects found (Figures 3, 6, and 7) confirm findings in a review by O'Sullivan et al. (2016) and in LCAs by Falkenstein et al. (2010) and Markwardt et al. (2017) dealing with climate effects of beverage cartons.

Along all value chain emissions, industrial processing activities from the pulp and paperboard mill had the largest climate warming effect, mainly due to high-energy consumption and use of chemicals. At this life cycle stage, climate efficiency can be substantially improved by carbon capture and storage, for example, by tall oil manufacturing or lignin extraction (Kuparinen et al., 2019). The fossil emissions from plantation operations were minor, with harvesting being the most emitting operation. Climate effects from transportation were minor considering all value chain emissions, contradicting findings by Judl et al. (2011). However, the emissions ratio found for the value chain of the eucalyptus pulp product was similar to that reported by Silva et al. (2015), Corcelli et al. (2018), and Sun et al. (2018). A 1-year time gap was assumed between production and incineration including the half-life of the beverage carton, adapted from Rüter et al. (2019). This led to minor influence of biogenic carbon storage in the beverage carton on the time dynamic climate effects. Alternatively, a landfill scenario could have been assumed as an end-of-life alternative, but landfilling is not common practice in the geographical area of the study (Sweden). In other geographical areas, it may be important to consider a landfill scenario. However, this would probably increase the uncertainty in the results, as carbon dynamics are quite variable (Sathre & O'Connor, 2010) and as ES is not possible as long as methane collection is not applied.

Substitution effects from material displacement (Figure 8) and offsetting energy (Figure 9) were substantial contributors to the overall climate impact. In contrast, total biogenic carbon sequestration and retention from standing biomass and soil in the eucalyptus plantation, and in the HWP, barely offset the dominating climate warming effect from all fossil value chain emissions, including the end-of-life incineration (Figure 7). This contradicts findings by Markwardt et al. (2017) that biogenic carbon can have a "significant role in the impact category climate change" of a beverage carton's life cycle. However, the magnitude of temperature cooling by the modeled eucalyptus plantation was similarly strong to that found in an

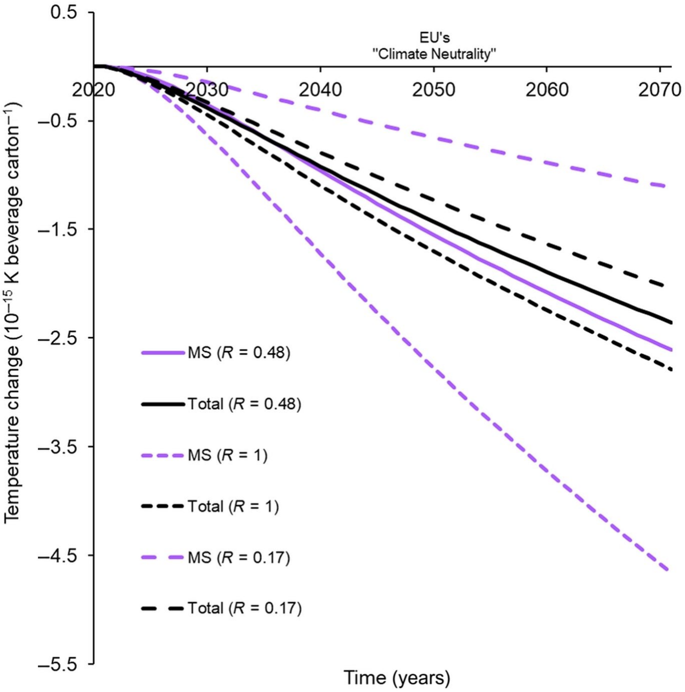


FIGURE 8 Temperature change in sensitivity analysis on changing the replacement rate (R), influencing material substitution (MS). The entire climate effect (Total) includes biogenic carbon, value chain emissions, and both energy and material substitution. The baseline represents moderate replacement ($R = 0.48$), while the other scenarios represent high ($R = 1$) and low ($R = 0.17$) replacement. *Note*: Energy substitution includes end-of-life emissions and forgone energy credit from avoided polyethylene terephthalate combustion. The results are shown from a landscape perspective

earlier time dynamic temperature change study of a eucalyptus product system (Porsö et al., 2016).

The calculated SFs accounted for production and the end-of-life stage. The range of values obtained was moderately higher to that reported by Soimakallio et al. (2016) for paperboard products (mean value -1.4 g C_{fossil} g^{-1} C_{biogenic}) and to the results from the meta-analysis by Leskinen et al. (2018) for packaging materials (-1.0 to -1.5 g C_{fossil} g^{-1} C_{biogenic}). However, Holmgren and Kolar (2019) obtained an even lower SF of -0.7 g C_{fossil} g^{-1} C_{biogenic} for pulp and paper products, possibly because they applied a proxy value. In contrast, higher values found in this study are mainly due to the large ES effects both in Uruguay and Sweden. The difference to the literature values highlights the overall variability in calculation of SFs and substitution effects, as discussed in more detail below. In addition, varying SFs among studies can emphasize the uncertainty connected to input parameters in LCAs of forest products which should be subjected to uncertainty analysis, for example, via Monte Carlo simulation (Sahoo et al., 2019). In this study, however, uncertainty was examined for the most climate influential part of the life cycle (i.e., the substitution effect) by sensitivity analysis of changing material replacement rates and varying marginal energy mixes.

4.2 | Methodological climate impact criteria and limitations

4.2.1 | Temporal assumptions and decisive factors for biogenic carbon effects

Time dynamic climate effects involve various assumptions, among which the chosen time horizon can be decisive for the results. In this study, 100 years on a hectare basis was chosen, to facilitate comparisons with other studies dealing with the climate effects of eucalyptus plantations. In addition, 50 years per unit of beverage carton was included, to highlight potential implications for the EU's committed climate neutrality target by 2050 (EC, 2020b). In general, defining shorter time horizons such as 50 years means truncating climate effects, which can disguise long-term benefits from biogenic carbon storage or a change where climate cooling becomes a warming effect. Thus, shorter time horizons can highlight immediate possible contributions of a (wood) product system for required action to meet short- or medium-term climate policy targets. Moreover, shorter time horizons lower the uncertainty in the results, due to decreased potential for future changes in, for example, technology, benchmark product characteristics, production processes, or end-of-life scenarios (Peñaloza et al., 2019). Overall, it is

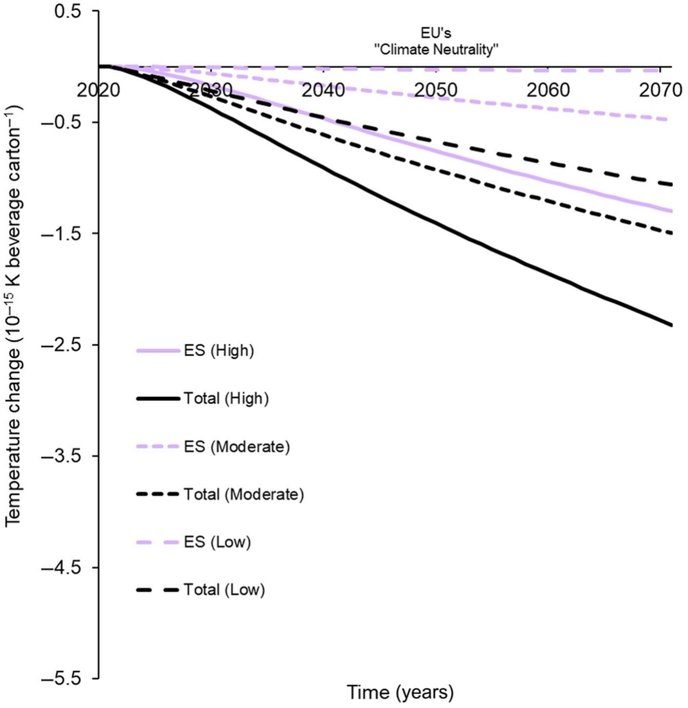


FIGURE 9 Temperature change in sensitivity analysis on changing the marginal Uruguayan electricity and marginal Swedish energy mix, influencing energy substitution (ES). The entire climate effect (Total) includes biogenic carbon, value chain emissions, and both energy and material substitution. The baseline represents a fossil- intense ES (marginal mix for 2020), while the other scenarios represent a moderately fossil-based ES (marginal mix for 2030) and a renewable-intense ES (marginal mix for 2040). *Note*: Energy substitution includes end-of-life emissions and forgone energy credit from avoided polyethylene terephthalate combustion. The results are shown from a landscape perspective

important to be aware of the consequences of a chosen time horizon for the climate effect results and consider whether an alternative choice might yield a different outcome (Lueddeckens et al., 2020).

Timing of biogenic carbon uptake before or after harvest is another important aspect for time dynamic climate assessments. In this study, accounting before harvest was applied, since it "represents reality better as the trees have to grow before they can be harvested" (Peñaloza et al., 2019) and since the objective was to advance knowledge of a product system's climate effects. In a landscape perspective modeling context, however, assumptions on former land use can be more decisive for the climate effects. In any case, there is consensus that applying a dynamic life cycle inventory and dynamic characterization increases the accuracy of LCA, regardless of the timing assumptions made (Lueddeckens et al., 2020).

A sustainable forestry system was assumed, for which a theoretical landscape perspective (i.e., a series of time-shifted stands) was applied (Berndes et al., 2016). This meant that all biogenic carbon from standing biomass was taken up from the atmosphere in year zero and no further fluxes were assessed. Thus, carbon equilibrium in the standing biomass was maintained over the rotation periods, in accordance with Sathre and O'Connor (2010). However, including the built-up phase of the plantation, which occurred before the start of the time horizon assessed here, could have substantially influenced overall biogenic carbon effects. This is because major biogenic carbon fluxes occur during this period due to biomass growth in the plantation, but were not assessed to ensure constant input–output flow in the time dynamic life cycle inventory. In contrast to a stand perspective, a landscape perspective can account for the simultaneous occurrence of silvicultural and subsequent manufacturing operations. It can thus be more realistic, increasing the policy relevance of the model. However, assumptions about production improvements (e.g., due to breeding, fertilization, etc.) and threats from future climate change were omitted here, and could add further policy relevance if included in the assessment.

Land use change and land use reference substantially influenced climate effects of biogenic carbon from standing biomass and the soil (Peñaloza et al., 2019). In this study, a LUC from grassland to eucalyptus plantation was assumed, while another option could be to rely on natural regeneration (continuation of grassland) (Helin et al., 2013; Koponen et al., 2018; Soimakallio et al., 2015). In any case, it is important to note that choosing the land use reference can cause a climate warming effect, for example, due to LUC from natural forest to plantations (Sathre & O'Connor, 2010). This highlights the major importance of avoiding conversion of natural forest into managed forest, as the former is considered superior in removing carbon from the atmosphere (Lewis et al., 2019). Similar to LUC from natural forest to plantations, conversion of grassland into eucalyptus plantations directly affects SOC stocks. In this study, SOC levels reached a quasi-long-term equilibrium, as also assumed in other studies on managed forests (Ericsson et al., 2013; Sathre & O'Connor, 2010). However, whether SOC levels under eucalyptus plantations remain constant over time is still uncertain (Behtrong et al., 2012; Cavalett et al., 2018; Fialho & Zinn, 2014; McMahon et al., 2019; Sandoval López et al., 2020), and thus implications for the climate. In addition, future biogenic carbon dynamics will probably be increasingly influenced by ongoing climate change, as climate-driven risks may fundamentally compromise (managed) forest carbon sinks (Anderegg et al., 2020), especially in regions such as South America (Payn et al., 2015).

From a product system perspective on the beverage carton, biogenic carbon played a minor role in the time dynamic climate effects. In another context where biogenic carbon from the plantation or forest could differ more substantially from a system perspective, defining the land use reference using more accurate data could be more important. In that case, time dynamic climate effects from LUC and biogenic carbon should consider the implications of indirect LUC (Faraca et al., 2019) and albedo (Sieber et al., 2019). However, calculation of these is still associated with great uncertainty and was thus omitted. Further research is needed on other forestry systems (e.g., Nordic forests) to increase knowledge on temporal and spatial variations in the role of biogenic carbon in time dynamic climate effects of wood product systems.

4.2.2 | The role of substitution effects

Substitution effects can be regarded as permanent (Sathre & O'Connor, 2010), in contrast to the temporary climate benefit from biogenic carbon storage. However, this approach requires decisive assumptions concerning both material and ES.

Material substitution effects may be substantially lowered if technologies of production or the properties of the substituted product (i.e., the PET bottle) improve (Leskinen et al., 2018). These developments could be accounted for in modeling by, for example, reducing the mass used for the PET bottle (Markwardt et al., 2017) or changing replacement rate of the wood product (Hammar et al., 2020). From a climate mitigation perspective, it is best to aim for replacing those nonrenewable materials which are most carbon intense and which are unlikely to become more efficient in their production (Suter et al., 2017; Verkerk et al., 2020). However, technological improvements in nonrenewable materials could also stimulate wood product manufacturers to improve production efficiency in their technology, for example, by improving heat recovery in paper mills (Corcelli et al., 2018).

Inherent properties of the materials, such as the LHV, can also be decisive for the climate effects during end-of-life incineration. Since the LHV of a PET bottle is higher than that of a beverage carton, avoided PET bottle incineration involves a forgone credit from ES which is greater than the credit derived from incinerating the beverage carton. Thus, the forgone credit from ES can result in a climate warming effect when regarded from a system perspective. In addition, climate cooling effects of ES from beverage carton incineration in Sweden are likely to decrease when the displaced future marginal energy mix becomes increasingly based on renewable energy via, for example, wind and solar energy. Such a development is likely for the entire EU, considering the commitment to ambitious renewable energy targets (Faraca et al., 2019). ES may eventually lead to a climate warming effect (Figure 9). However, the energy mix substituted is a normative definition and can differ between, for example, the current mix, the marginal mix, or a changing mix (Knauf et al., 2016). In any case, bioenergy from combustion of wood products can be important in balancing future energy fluctuations from solar and wind power (Arasto et al., 2017). By applying both a climate mitigation and a renewable energy supply perspective, bioenergy can thus be a crucial contributor to achieving aligned policy ambitions, such as the EU's climate neutrality target.

However, to increase the policy relevance of substitution in a growing bioeconomy, "leakage effects" should be considered in the climate assessment. This includes potential emissions shifts induced by shifted activities from sustainable forestry to less sustainably managed forestry (Leskinen et al., 2018) or cross-sectoral shifts of avoided climate burdens (Harmon, 2019).

In general, substitution effects of wood products are a highly debated issue and there is currently no consistent basis for assessment. Some highlight the potentially strong climate mitigation effect of substitution (Leskinen et al., 2018; Sathre & O'Connor, 2010), while others argue the opposite (Harmon, 2019; Leturcq, 2020). In fact, it is claimed that the long-term climate mitigation benefits from substitution may have been overestimated by two- to 100-fold, for example, through the frequent assumption of keeping SFs constant over time and omitting "leakage effects" (Harmon, 2019). In this context, the strongest climate mitigation effect for wood products may not be induced by increasing harvest levels (Leturcq, 2020). Irrespective of this, effective substitution should be focused on increasing wood application in the construction sector, but accounting for substitution credit will still only be valid if an "increase in wood product consumption implies verifiably a global reduction in non-wood productions" (Leturcq, 2020). Without policies ensuring the absence of "leakage effects," substitution benefits from wood products can be limited (Harmon, 2019).

This study confirmed the great variability in substitution effects and associated SFs. Sensitivity analysis on varying replacement rates and differing marginal energy mixes was conducted to alleviate the shortcomings of static substitution over time. However, to improve the validity of substitution effects (of wood product systems), dynamic substitution factors covering time-dependent changes (in e.g., energy mixes or technological advances in a product) should be used in future assessments, as implemented by Brunet-Navarro et al. (2021).

4.2.3 | Cascading wood use

Directly connected to substitution effects is cascading use of wood products. Whether cascading leads to definite increased climate cooling effects is debated (Berndes et al., 2016; Höglmeier et al., 2014, 2015; Leskinen et al., 2018; Sathre & Gustavsson, 2006; Suter et al., 2017). In a meta-analysis, Thonemann and Schumann (2018) found that around half of the studies reviewed indicated a positive effect from cascading on the climate and the other half a mixed effect. Moreover, perceptions vary on whether additional cascading steps naturally lead to additional climate benefits. In this regard, Faraca et al. (2019) concluded that the largest climate benefits are obtained in the first cascade step, "when the quality of the resource is at its highest point." This highlights the importance of choosing quality-oriented recycling. In the present study, a pulp product was investigated, which limited cascading use. Nevertheless, it was shown that the energy recovery step brought a substantial potential benefit to the overall climate effects of the product.

Irrespective of its controversial climate implications, cascading wood use can bring great benefits in terms of land use (Höglmeier et al., 2015; Sathre & Gustavsson, 2006; Suter et al., 2017). In fact, it is key to consider other impact categories apart from climate effects, such as water consumption (Ferraz et al., 2019) or biodiversity aspects (Pozo & Säumel, 2018) when assessing the environmental sustainability of a eucalyptus wood product system. Since only 8% of the managed forests in South America are under PEFC or FSC certification (Sikkema et al., 2017), there is an urgent need for scrutiny of environmental sustainability in LCA of the European wood supply (O'Sullivan et al., 2016).

4.2.4 | Suitability of the climate metric chosen

The climate metric chosen can substantially influence the outcome of a time dynamic climate impact assessment (Breton et al., 2018). Apart from the AGTP, alternative climate metrics also accounting for time dynamics are, for example, the GWP_{bio} (Cherubini et al., 2011), or time-dependent radiative forcing (Sathre & Gustavsson, 2012), which are further "up" the cause–effect chain from GHG emission to climate change impacts (Breton et al., 2018; Myhre et al., 2013). The focus in this study was on AGTP, which accurately incorporated time-dependent carbon fluxes of biomass-based systems. Thus, the metric is reliable and flexible, and provides a better understanding of biogenic carbon effects on the climate in a long- and short-term perspective, as also stated by Peñaloza et al. (2019) and Garcia et al. (2020). Regarding substitution effects, the AGTP metric functioned well in accounting for potential time-dependent emission savings. In future assessments, AGTP would therefore be a suitable metric to include recommended dynamic substitution factors to account for future changes concerning substitution-related aspects, such as improved production efficiency.

4.3 | Potential relevance for climate policy making

Biogenic carbon and substitution are both regarded as important pillars in climate-smart forestry for policy making of bio-based products in a growing bioeconomy (Nabuurs et al., 2018). This study revealed a potential temperature change range from $-0.8 \cdot 10^{-15}$ to $-1.8 \cdot 10^{-15}$ K per unit of beverage carton until the year 2050, based on all results from the sensitivity analysis performed. Considering an average annual output volume of a European liquid packaging board mill of approximately one million tons (Stora Enso, 2019), a potential temperature change range from $-2.9 \cdot 10^{-10}$ K to $-6.2 \cdot 10^{-10}$ K could thus be reached for 2050 by producing and using beverage cartons over PET bottles. As CO_2 emissions intensity from the European paper industry has decreased by approximately 25% since 1990 already (Corcelli et al., 2018), the results of this study can thus highlight the additional climate benefit of a rapid replacement of fossil-based PET bottles by the use of bio-based beverage cartons.

5 | CONCLUSIONS

The forest sector can play a pivotal role in mitigating climate warming, but assessing the actual climate effects of a wood product system is complex and requires a holistic approach. This study revealed that inclusion of biogenic carbon and substitution effects improved the holistic and time dynamic climate effect assessment of a bioeconomically promising wood product, a beverage carton. The results showed that substantial climate warming from value chain emissions was barely offset by biogenic carbon from the eucalyptus plantation, including standing biomass and SOC, as well as short carbon storage within the HWP. In contrast, effects from MS and displacing marginal energy mixes converted the time dynamic temperature change into considerable climate cooling. Sensitivity analysis involving varying replacement rates of the beverage carton and differing marginal energy mixes showed great variability of substitution effects for both substitution factors and temperature change. Potential relevance for climate policy making was evident from a climate cooling effect of $-0.8 \cdot 10^{-15}$ to $-1.8 \cdot 10^{-15}$ K per unit of beverage carton by 2050. Production and use of wood-based beverage cartons instead of PET bottles can therefore contribute to mitigating climate warming effects. Further holistic time dynamic climate assessments on alternative forestry systems (e.g., Nordic forests) are needed to advance knowledge on the role of biogenic carbon, including dynamic assessment of substitution effects.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

MS performed the LCA modeling and led the writing process. TH made substantial contributions to the methodological approach, the conception of the study, and interpretation of data. JS contributed considerably by raising important aspects about the study's concept and discussion. MSe modeled primary data into soil organic carbon stocks using the dynamic soil carbon model Yasso 15. PAH made substantial contributions to conception and design of the study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information of this article.

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ORIGINAL PAPER

Nordic forest management towards climate change mitigation: time dynamic temperature change impacts of wood product systems including substitution effects

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Abstract

Climate change mitigation trade-offs between increasing harvests to exploit substitution effects versus accumulating forest carbon sequestration complicate recommendations for climate beneficial forest management. Here, a time dynamic assessment ascertains climate change mitigation potential from different rotation forest management alternatives across three Swedish regions integrating the forest decision support system Heureka RegWise with a wood product model using life cycle assessment data. The objective is to increase understanding on the climate effects of varying the forest management. Across all regions, prolonging rotations by 20% leads on average to the largest additional net climate benefit until 2050 in both, saved emissions and temperature cooling, while decreasing harvests by 20% leads to the cumulatively largest net climate benefits past 2050. In contrast, increasing harvests or decreasing the rotation period accordingly provokes temporally alternating net emissions, or slight net emission, respectively, regardless of a changing market displacement factor. However, future forest calamities might compromise potential additional temperature cooling from forests, while substitution effects, despite probable prospective decreases, require additional thorough and time explicit assessments, to provide more robust policy consultation.

Keywords Forest management · Climate effects · Forest-based bioeconomy · Sweden · Substitution effects

Introduction

The forest-based bioeconomy of the European Union (EU) is considered a key part of climate change mitigation strategies both by increasing carbon stocks in forests via carbon dioxide (CO_2) sequestration and in harvested wood products (HWP), and by using wood to substitute more greenhouse gas (GHG) intensive materials and energy sources (EC 2021). However, increasing HWP carbon pools and enhancing wood-based substitution through increased wood harvests conflicts with increased forest carbon sequestration.

This highlights the strongly debated trade-off between increasing forest carbon sinks on the one hand and promoting wood substitution on the other (Dugan et al. 2018; Seppälä et al. 2019; Hurmekoski et al. 2020; Jonsson et al. 2021; EC 2021). For assessing this trade-off, an integrative system perspective is thus required to reveal net climate benefits in assessments of forest-based climate change mitigation options.

Within this given trade-off between forest-based carbon sequestrations on the one hand and wood-based substitution and HWP carbon pools on the other lies a strong temporal dimension. Many studies that assess various combinations of increased harvest levels and resulting shifts in the production of HWP commodities conclude that within a short to medium time horizon, the climate benefit from the carbon sink in the productive forest land will exceed additional mitigation from substitution effects and an increased HWP pool

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resulting from increased harvests (Lundmark et al. 2014; Rüter et al. 2016; Matsumoto et al. 2016; Valade et al. 2018; Seppälä et al. 2019; Kalliokoski et al. 2020; Soimakallio et al. 2021; Jonsson et al. 2021; Skytt et al. 2021; Hiltunen et al. 2021; Moreau et al. 2022). If the product portfolio remains stable (i.e. shares among relative HWP distribution keep constant), this conclusion holds also when high substitution effects are assumed (i.e. a displacement factor of < 2.4 Mg C Mg C^{-1}), as mentioned by Seppälä et al. (2019) and Kalliokoski et al. (2020). Within longer time horizons, however (i.e. from minimum 30 years to over 100 years), climate benefits from wood use and associated substitution effects are found to be larger than the net decrease in forest carbon sinks (Lundmark et al. 2014; Skytt et al. 2021; Gustavsson et al. 2021) when assuming static and stable substitution effects over time.

Substitution effects and displacement factors (DFs) vary strongly depending on geographical scope, system boundary, life cycle inventory (LCI) data, and time horizon applied (Brunet-Navarro et al. 2021; Myllyviita et al. 2021). Further, climate change mitigation from wood substitution can be assumed to change in the future, because of, e.g. increased renewable energy use, enhanced production efficiency, or bioenergy and carbon capture and storage (BECCS) (Creutzig et al. 2015). In fact, according to Brunet-Navarro et al. (2021), material substitution effects could decrease by 33% already by 2030, and even by 96% until 2100 when set proportionally to gross anthropogenic CO_2 emission reductions as required to reach the Paris Agreement (Rockström et al. (2017). This stresses expiration of wood product substitution benefits over time.

In Sweden, the forest sector historically plays a key economic role (Lundmark et al. 2013) and is aligned to national environmental quality targets (SME 2019) within the EU's bioeconomy strategy (EC 2018). Swedish forest management is characterized by stable delivery of wood products via extensive long rotation forestry (Eyvindson et al. 2021). Clear-cut harvest and even-aged stand structures dominate the production forest (Egnell and Björheden 2015) with minimum rotations ranging from 45 years in the south to over 100 years in northern Sweden (SME 2019). Over the last century, standing volume, productivity and sustainable harvest levels increased continuously (Lundmark et al. 2013; SFA 2014; Klapwijk et al. 2018; Giuntoli et al. 2020).

However, current Swedish clear-cut forest management is being increasingly debated on its capacity to provide other ecosystem services than wood production, with climate change mitigation at the forefront. The alternatives most frequently put forward to increase the climate benefits of forestry encompass: bioenergy usage of decaying forest residues (tops and branches) (Pukkala 2014; Camia et al. 2021; Eggers et al. 2020), afforestation of set-aside land (Egnell and Björheden 2015), increased harvest rates (Gustavsson et al. 2017), genetically improved seedlings and intensive fertilization (Subramanian et al. 2019; Nilsson et al. 2011), extending rotation periods (Liski et al. 2001; Zanchi et al. 2014; Felton et al. 2017; Eggers et al. 2019; Lundmark et al. 2018; Pingoud et al. 2010), and increased sawlog harvests for augmented long-lived HWP application to substitute emission intense building materials (Churkina et al. 2020; Howard et al. 2021; Dugan et al. 2018; Pingoud et al. 2010).

The effectiveness of different forest-based climate change mitigation alternatives depends largely on the general forest productivity which to a great extent is determined by local climate, soil conditions, and forest characteristics, not the least the age class distribution, i.e. younger forests grow faster than old ones (Petersson et al. 2021). Hence, to more unambiguously analyse climate change mitigation trade-offs between forest carbon storage and increased harvest to promote substitution of GHG intensive non-wood products, regional-level assessments are needed, integrating the interconnected forest eco- and technosystem including the substituted system to avoid conflicting and misleading policy recommendation in order to reach net climate benefits (Smyth et al. 2017; Dugan et al. 2018; EC 2021; Jonsson et al. 2021). In that context, a more nuanced analysis of wood substitution is required to better capture and depict changes in substitution effects following shifts in forest management and ensuing changes in the harvest compositions. Thus, more detailed substitution effect breakdowns are needed in assessments integrating forest eco- and technosystems, to advance over the more aggregated analysis of substitution effects resulting from changed forest management in the studies of, e.g., Cintas et al. (2017), Skytt et al. (2021), or Moreau et al. (2022). The system perspective (EC 2021) further requires inclusion of temporal considerations for which methodological approaches of life cycle assessment (LCA) (ISO 2006a, 2006b) including time dynamic effects (also referred to as time-dependent effects) are appropriate and established methods (Ericsson et al. 2013; Levasseur et al. 2013; Hammar et al. 2019; EC 2021; Hiltunen et al. 2021).

This study provides an integrative time dynamic assessment at regional level, using LCA data to analyse the climate effects of different forest management strategies from a system perspective (EC 2021), to assess the climate change mitigation potential from alternative Swedish rotation forest management. In doing so, the study specifically contributes to the field in (i) deriving detailed substitution effects for an entire HWP portfolio, analysing how these effects change consequential to different forest management regimes and (ii) by advancing common climate assessments of wood product systems given in CO_2 equivalent (CO_2-eq) fluxes into the absolute global temperature change potential (AGTP) that displays climate impacts in terms of temperature change over time (Myhre et al. 2013). By benchmarking

Table 1 Forestry data of all Swedish regions across the North–South climate gradient

Property	Unit	Norrbotten (North)	Värmland (Central/South)	Kronoberg (South)	References
Productive Forest Area	1000 ha	3 930	1 345	666	NFI 2014–2018
Mean Volume (productive land)	$m^3\ ha^{-1}$	110	178	151	NFI 2014–2018
Average Productivity (Bonitet)	$m^3\ ha^{-1}\ yr^{-1}$	2.5	6.6	9.2	NFI 2014–2018
Average Mean Age	years	76	54	48	NFI 2014–2018
Average Minimum Final Felling Age	years	85	64	58	NFI 2014–2018
Average Final Felling Age	years	116	108	99	NFI 2014–2018
Productive Forest Land for Logging Residue Extraction	%	20	35	45	Adapted from Eggers et al. (2020)

Productive forest land here includes voluntarily and formally set-aside areas

all forest management scenarios to an initial reference forest management across a climate gradient, we seek to increase the understanding as to which, how, and when climate effects of different forest management approaches within a forest-based bioeconomy occur.

Materials and methods

Geographical scope and system boundaries

The study is set in the geographical regions Norrbottens län (67° 08′ 8.98″ N 18° 30′ 3.52″ E), Värmlands län (59° 44′ 59.99″ N 13° 14′ 60.00″ E), and Kronobergs län (56° 14′ 36.06″ N 14° 22′ 51.97″ E) to cover a large latitudinal gradient and thus forest productivity range across Sweden. Table 1 summarizes key information of the initial state of each region, based on Swedish National Forest Inventory (NFI) data from 2014 to 2018. On productive forest land ($>1\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$), there exist voluntarily and formally set-aside areas which were excluded for the analysis based on statistics from the Swedish Forest Agency (SFA) SFA (2021a) and NFI data. For detailed information on simulated forest characteristics of all regions, including forest age class and species distribution see the Supplementary Material.

The system boundary for each region is shown in Fig. 1. Climate effects are primarily determined by the forest ecosystem, which depends on the forest management strategies

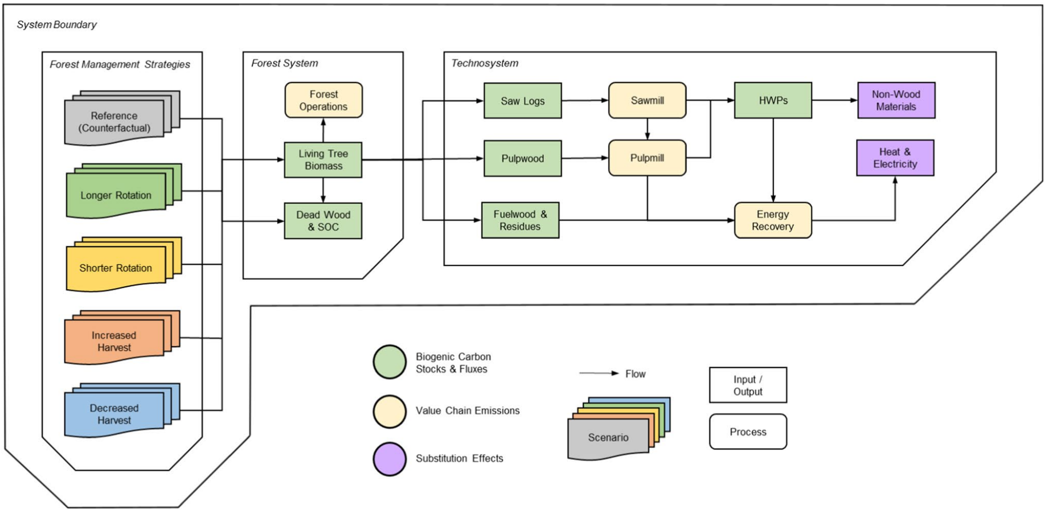


Fig. 1 System boundary for each region including the forest ecosystem and the technosystem influenced by different forest management scenarios. HWP = Harvested Wood Product, SOC = Soil Organic Carbon

and the distribution of biogenic carbon over time ("Section Forest system"). Biogenic carbon from sequestration and decay is allocated between living tree biomass, soil organic carbon (SOC), and dead wood. Forest harvest volumes divide into sawlogs, pulpwood, fuelwood and cullwood (in the following summarized as fuelwood), and harvest residues (branches and tops) which enter the wood product technosystem ("Section Technosystem"). Here, retention, decay and associated biogenic carbon emissions from HWPs are accounted for ("Section HWP portfolio and value chain emissions"). The technosystem comprises processing of harvest volumes into final HWPs in saw and pulp mill facilities, and into energy in a combined heat and power (CHP) plant. Along each wood product value chain, fossil CO_2, methane (CH_4) and nitrous oxide (NO_2) emissions were considered from "cradle to grave" ("Section Substitution effects") and transformed into CO_2-eq using the global warming potential (GWP_{100}) with a 30-fold cumulative radiative forcing of fossil CH_4 and a 265-fold stronger effect of N_2O than that of CO_2 (Myhre et al. 2013). Finally, substitution effects were considered based on a certain HWP portfolio ("Section Climate impact metrics").

Forest system

Forest ecosystem & forestry modelling

The forest management scenarios and biogenic carbon outputs of the forest ecosystem were modelled via the Heureka scenario analysis software RegWise (Wikström et al. 2011) using empirical NFI-based forest data from 2014 to 2018. Heureka RegWise simulates alternative forest management strategies by deterministic models on species-specific forest growth and decay functions, adjustment of silvicultural operations such as final harvest or changing rotation length. Biogenic carbon stocks from living trees (standing biomass) are calculated by biomass expansion factors from the different aboveground compartments of the trees (stem, bark, branches, leaves/needles), and the belowground parts (roots and stumps). SOC is modelled via continuous soil organic matter decomposition by the Q-model that is integrated in Heureka. The carbon stock in dead wood is calculated by additional volume inflow of dead organic matter from tree mortality using an exponential decay rate (Harmon et al. 2000).

Output variables of Heureka simulations for this study were biogenic carbon (Mg C) in standing biomass, dead wood, and SOC, and harvest volumes (m^3) from sawlogs, pulpwood, fuelwood, and logging residues. Harvest volumes and relative distribution among sawlogs, pulpwood, fuelwood, and harvest residues varied depending on the forest age distribution and forest management scenario. Partitioning of sawlog, pulpwood, or fuelwood is predefined in Heureka based on stem diameters greater than 13 cm, 13–5 cm, and smaller than 5 cm, respectively. Values were given in five-year intervals and transformed via interpolation and conversion factors into annual carbon equivalents considering a coniferous softwood density of 415 kg m^{-3} for sawlogs and 400 kg m^{-3} for pulp- and fuelwood, and a dry wood carbon content of 50% (FAO et al. 2020). Given the mass ratio from C to CO_2 of around 1 to 3.67, this equals 732–760 kg CO_2 m^{-3} harvested.

The interpolated and converted values were subsequently used for modelling the technosystem which was kept similar for all regions and forest management scenarios. The time horizon was set to 200 years to include the effects from multiple rotations into the analysis. To assess net impacts on climate change and show additionality, a valid counterfactual "business as usual" (reference) scenario is key to demonstrate how alternative scenarios alter emissions which would have instead occurred (Chomitz 2002). The forest management scenarios for all regions (Table 2) thus include a reference which acted as the counterfactual "business as usual" scenario to prove additionality, and four alternatives: a longer and shorter rotation scenario, and an increased and decreased harvest scenario, to show climate effects from a more and less intensive forestry.

Forest management scenarios

The reference scenario represents recent clear-cut rotation forest management in Sweden as the dominating forest

Table 2 Forest management scenarios on the productive forest land in all regions

Management Practice	Scenarios				
	Reference (Counterfactual)	Longer Rotation	Shorter Rotation	Increased Harvest	Decreased Harvest
Management System	Rotation Forestry				
Harvest Level (% of growth)	83%	83%	83%	100%	66%
Rotation Length (% of min. relative final felling age)	100%	120%	80%	100%	100%
Regeneration	Planting				

management practice in each region. The harvest level amounts to 83% of the growth rate on productive forest land according to the Swedish forest reference level (FRL) (SME 2019). Regeneration under productive forest land occurs via planting, and the rotation length is based on the relative final felling age defined by the Swedish Forestry Act. Thinning is performed according to good practice from the Swedish Forest Agency (SFA 2015). Tree and stump retention after harvest was modelled in accordance with forest certification standards and followed sustainable harvest levels (Jong et al. 2017; SME 2019). Potential final felling area for extracting logging residues was given only under spruce-dominated stands based on the ranging proportions between northern (20%) and southern Sweden (60%) (Eggers et al. 2020). Logging residue extraction comprised 100% tops, 83% of branches, and 38% of needles and was performed only on dry and semi-dry soils, while no stumps were extracted to comply with recommendations from the Swedish Forest Agency (Claesson et al. 2015). Fertilization regimes in Norrland and Värmland amounted to 10,400 ha year^{-1} and to 700 ha year^{-1} in Kronoberg based on average past decade fertilization regimes in Norrland, Svealand, and Götaland, respectively (SFA 2021b).

The longer and shorter rotation scenario was modelled similarly to the reference scenario except for prolonging or curtailing the minimum relative final felling age by ± 20%, respectively. The increased and decreased harvest scenario differed from the reference in terms of an increased or decreased harvest rate by ± 20% reaching a harvest level of 99.6%, and 66% of the growth rate on productive forest land. No climate model and storm model from Heureka was applied in the simulations as both insufficiently represent probable climate change-induced developments.

Table 3 HWP portfolio and substitution portfolio, adapted from Hurmekoski et al. (2020). Replacement rate (R) is expressed in mass units of replaced product per one mass unit of HWP end-use

HWP	End-use	Replaced product	Functional unit	Replacement rate (R)	DF (Mg C Mg C^{-1})	References
Sawnwood	Construction	Concrete Steel	Application in Multi-Family Housing Residentia	9.7 0.2	0.8	Peñaloza et al. (2016), Mehr et al. (2018), Piccardo and Gustavsson (2021)
	Packaging (Pallets)	HDPE	EU Norm Pallett	0.2	0.4	EPAL (2021), APLP (2021)
	Furniture	Steel, PP, PUR, glass, aluminium, PVC	Average Furniture Article	0.1	0.0	Geng et al. (2019)
	Other	-		-	-	
Plywood + Fibreboard	Construction	Gypsum, Mineral Wool, Plaster	Application in Multi-Family Housing Residential	0.2	-0.6	Peñaloza et al. (2016), Mehr et al. (2018), Piccardo and Gustavsson (2021)
	Other	-		-	-	
Pulp & Paper	Graphical Paper	-		-	-	
	Paperboard	PET	Average Paperboard Packaging	0.5	1.1	SCB (2021)
	Viscose	Cotton, Polyester	Mass Based	1	0.4	Peñaloza et al. (2019)
	Other	-		-	-	
CHP	Heat & Electricity	Natural Gas	Energy Content Based	1	0.4	Gode et al. (2011)
Biofuel	HVO	Diesel		1	1.1	Gode et al (2011), Hallberg et al. (2013), Danish Energy Agency (2017)
Weighted Average (DF$_m$)					0.6	

HWP = Harvested Wood Product, CLT = Cross-Laminated Timber, HDPE = High-Density Polyethylene, PP = Polypropylene, PUR = Polyurethane, PVC = Polyvinylchloride, PET = Polyethylene terephthalate = Combined Heat and Power, DF = Displacement Factor, DF$_m$ = Market Displacement Factor. For more information see the Supplementary Material

Technosystem

HWP portfolio and value chain emissions

Within the technosystem, sawlogs, pulpwood, fuelwood and harvest residues were classified for different applications, comprising a certain HWP portfolio which was further defined by HWP end-uses (Table 3). A Sankey diagram in the Supplementary Material further illustrates the distribution within the portfolio. Sawlog-based HWPs were distributed into 91% sawnwood, 1% plywood, 8% fibreboards and particleboards (in the following summarized as fibreboards), based on SFA (2014). From the 91% sawnwood, 69% were used as construction wood, 19% as packaging wood mainly in form of pallets, 3% as furniture, and 9% as other, undefined products (Hurmekoski et al. 2020). The share of 69% construction sawnwood was further divided into 85% timber light-frame construction, 7.5% cross-laminated timber (CLT), and 7.5% glued laminated timber (glulam) (Rudenstam 2021). Out of the 9% plywood and fibreboards share, 41% were used for construction and 59% for other, unspecified end-uses, based on Hurmekoski et al. (2020). Residues in form of shavings and wood chips from sawnwood production ended up as feedstock in pulp mills, while sawdust and bark were used as fuelwood.

Pulpwood supplied either chemical or mechanical pulp mills with a relative distribution of 75% and 25%, respectively (Skogsindustrierna 2021). Distribution of cellulose-based pulpwood HWP end-uses from the chemical pulp mill comprised 38% paper, 51% paperboard, 2% viscose, and 9% other, based on Skogsindustrierna (2021), CEPI (2020) and Hurmekoski et al. (2020). The remaining pulpwood components hemicellulose, lignin, and extractives were used in form of black liquor for internal energy recovery. A small fraction of crude tall oil (CTO) was extracted from black liquor (0.04 Mg CTO Mg pulp^{-1}) (Staffas et al. 2013) and used for hydrogenated vegetable oil (HVO) production, whose properties and emissions were adapted from Gode et al. (2011), Hallberg et al. (2013) and Danish Energy Agency (2017). Viscose-related emissions were taken from Peñaloza et al. (2019). In the mechanical pulpmill, pulpwood was entirely used to produce thermo-mechanically and stone-grounded paper with shares of 50% each.

All harvest residues, residual paper, and fuelwood were assumed to be used for energy recovery in a CHP plant with a heat efficiency of 45% and an electricity efficiency of 30% (EC 2011).

Temporary carbon storage in HWPs was accounted for and calculated with half-life times of 35, 25, and 2 years for sawnwood, wood panels, and pulp-based products, respectively (Rüter et al. 2019). For fuelwood, harvest residues, and by-products within the pulp mills, a half-life time of one year was applied.

Fossil value chain emissions from cradle to grave of CO_2, CH_4, and N_2O were based on process-specific ecoinvent LCI data (version 3.7.1) (Wernet et al. 2016) (Supplementary Material) unless otherwise stated. Emissions connected to a use-phase of all HWP end-uses and the substituted applications were considered similar and thus negligible, including calcination and carbonation processes (Gustavsson et al. 2017, 2021). The end-of-life stage of all HWP end-uses represented energy recovery via incineration within CHP plant facilities which created an energy substitution effect, in addition to the material substitution.

Substitution effects

The portfolio of HWP end-uses replaced a counterpart portfolio of non-wooden construction materials, plastic products, as well as energy sources whose emissions were also based on LCI ecoinvent data (Wernet et al. 2016) (Supplementary Material) unless otherwise stated.

Meeting the same function among non-wood and wood-based products often requires varying mass amounts of each. For construction materials, this can result in substantially different mass replacement ratios (in the following also called replacement rates) (Cordier et al. 2021), e.g., depending on the building type (Peñaloza et al. 2019), or physical properties such as density or the thermal conductivity (Schulte et al. 2021a). Given the variety of construction materials covered in this study, mass replacement rates according to multiple materials were adapted from Peñaloza et al. (2016), Mehr et al. (2018), and Piccardo and Gustavsson (2021) (Supplementary Material). Sawnwood used in timber light frame, CLT, and glulam timber frame multi-storey residential buildings was assumed to substitute for concrete and steel (Cordier et al. 2021), and plywood and fibreboards replaced gypsum boards, plaster, and mineral insulation materials.

Sawnwood used for packaging (pallets) (25 kg pallet^{-1}) was assumed to replace high-density polyethylene (HDPE) pallets (5.5 kg pallet^{-1}) based on EPAL (2021) and APLP (2021). Wooden furniture replacement built on a representative average of non-wooden furniture, consisting out of steel (67%), polypropylene (PP) (11%), polyurethane foam (PUR) (10%), glass (5%), aluminium (5%), and polyvinylchloride (PVC) (2%) based on Geng et al. (2019). Paperboard packaging replacement of plastic packaging considered an average plastic packaging recycling rate of 67% and recycling from wood packaging to be 41% (SCB 2021). Wood-based cellulose fibre in form of viscose was assumed to replace cotton fibre and polyester (PET) fibre in equal shares, with a simple mass replacement ratio of one to one, similar to Peñaloza et al. (2019). Graphic paper was not assigned any replaceable product, except for energy substitution at the end of life.

Energy substitution was included from incineration of fuelwood and all waste wood products at their end-of-life within a CHP plant to produce heat and electricity, with efficiencies of 45%, and 30%, respectively (Börjesson et al. 2010; EC 2011). Heat and electricity from waste wood, paper and cardboard, and viscose with lower heating values (LHVs) of 16 MJ kg^{-1} and 17 MJ kg^{-1}, respectively (Östlund et al. 2015; ECN 2021a, 2021d) replaced energy recovery within similar CHP facilities from incineration of plastic packaging and cotton textile with LHVs of 40 MJ kg^{-1} and 16 MJ kg^{-1} (ECN 2021c, 2021b), respectively. This resulted in reduced consumption of natural gas as the fossil energy substitute. Fuel replacement was included from diesel towards HVO use. GHG emissions from natural gas and diesel were based on Gode et al. (2011).

Substitution effects were estimated as the product sum of HWP end-use shares, HWP end-use production volumes, LCI emission data for the substituted materials, and finally, mass replacement rates in the different end-uses. Value chain emissions of HWP end-uses were recorded separately in the overall GHG net emission calculations. While substitution effects were accounted for as avoided ("negative") emissions, forgone substitution effects that were not realized, e.g., due to decreased harvest, acted as an emission source. Fossil emissions from the HWP end-use value chains and from substitution effects remained constant over the entire time horizon, albeit this simplifies and neglects that both should be subject to drastic future changes, as mentioned earlier.

Displacement factors & sensitivity analysis

The magnitude of the entire substitution effects can be decisive for whether and when an entire wood product system acts as a CO_2-eq source, or sink. For this purpose, a market displacement factor (DF_m) (Hurmekoski et al. 2021) was calculated from the product DFs (Sathre and O'Connor 2010), to facilitate comparison with similar studies.

The DF_m consisted of the weighted DFs of each HWP end-use with given replacement rates (Table 3) that were assessed similarly as in Hammar et al. (2020) and Schulte et al. (2021b):

$$\mathrm{DF}_x = \frac{\mathrm{GHG}_{\mathrm{non-wood}} \cdot R - \mathrm{GHG}_{\mathrm{wood}}}{\mathrm{WU}_{\mathrm{wood}} - \mathrm{WU}_{\mathrm{non-wood}} \cdot R} \tag{1}$$

where the displacement factor DF of x, a certain HWP end-use, is given in Mg C_{fossil} Mg^{-1} $C_{biogenic}$, $GHG_{non\text{-}wood}$ and GHG_{wood} represent the GHG emissions from cradle to grave of the substituted and wood product, respectively, expressed in mass units of carbon corresponding to the CO_2-eq of the emissions. WU_{wood} and $WU_{non\text{-}wood}$ denote the amount of wood used in the wood product and substituted product, respectively, also given in mass units of carbon, and R is the replacement rate (Table 3 and Supplementary Material). The market displacement factor DF_m was further calculated as

$$\mathrm{DF}_m = \frac{\sum_{x=1}^{n} \mathrm{DF}_x \cdot W_x}{\sum_{x=1}^{n} W_x} \tag{2}$$

where W_x is the weight, or amount of each HWP end-use x as a share of the total HWP end-use amount (Hurmekoski et al. 2021).

Note that multiplication of the DF_m with harvest volumes is thus not possible as it is derived from the final HWP end-use amount, not the initial harvest volume.

To address connected uncertainty and impact on the results, a sensitivity analysis doubled and halved replacement rates of all HWP end-uses which increased and decreased the DF_m, respectively.

Climate impact metrics

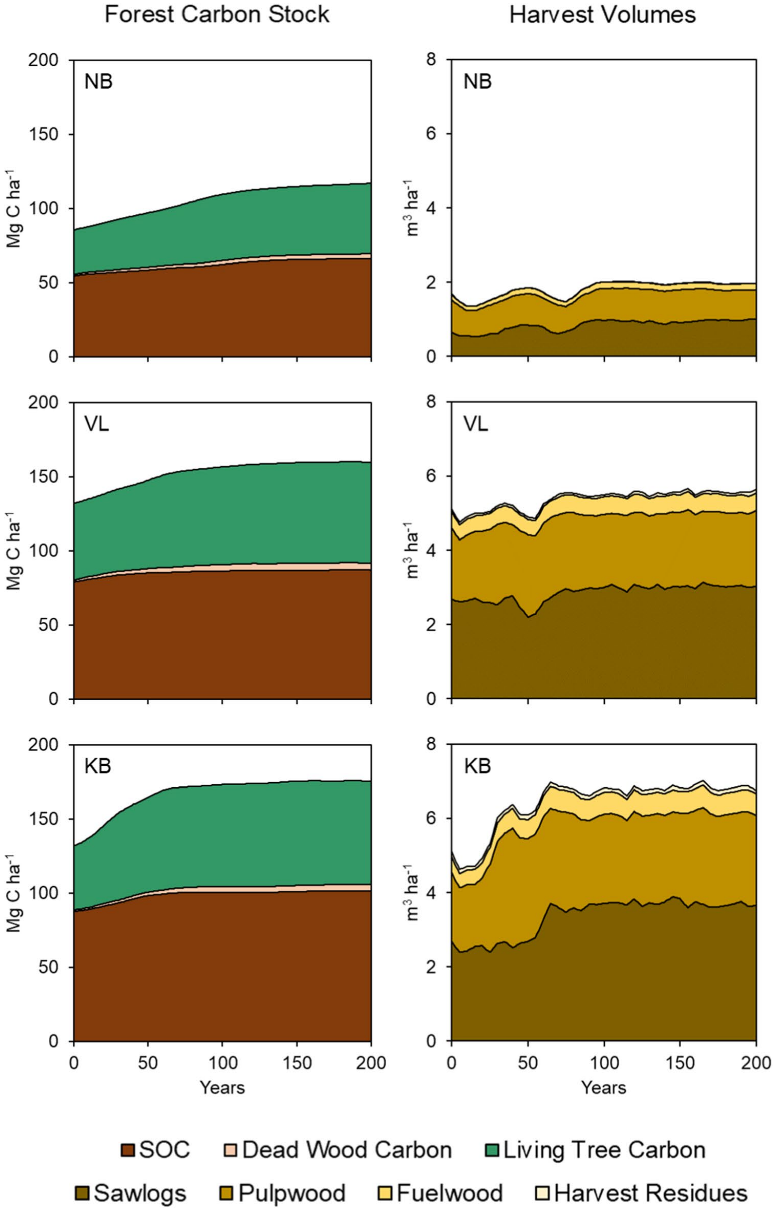
Climate effects from GHG fluxes were calculated using the global warming potential GWP_{100} and the AGTP (Myhre et al. 2013). The GWP_{100} is the cumulative radiative forcing (RF) of other GHGs, here CH_4 and N_2O, relative to the RF of CO_2 for a given time frame, i.e. 100 years (Joos et al. 2013). The metric yet misses to account for the timing of emissions along the assessed time horizon and associated dynamics in the atmosphere.

The AGTP is the response in global mean surface temperature at a certain point in time generated by a change in radiative forcing due to a GHG pulse emission expressed in degrees of kelvin (K). The AGTP was calculated based on annual GHG fluxes from CO_2, CH_4, and N_2O. The perturbation lifetime of CO_2 is based on the Bern carbon cycle model (Joos et al. 2001, 2013), where the molecule remains airborne until it is taken up by oceans or the biosphere. For CH_4 and N_2O, average perturbation lifetimes were 12.4 and 121 years, respectively (Myhre et al. 2013). The AGTP is described by:

$$\mathrm{AGTP}_x(H) = \int_0^H RF_x(t) R_T(H - t)\mathrm{d}t \tag{3}$$

where radiative forcing (RF), expressed in W m^{-2}, and the climate response function (R_T) constitute a convolution over the time horizon assessed (H) by a change in RF from a pulse emission of a GHG x. Thus, AGTP accounts for the timing of GHG emissions and their perturbation lifetimes which enables the assessment of time-dependent dynamics within (time dynamic) climate effects. In this study, the term AGTP is used synonymously with the term temperature change.

Fig. 2 Simulated forest carbon stock (Mg) and harvest volume (m^3) developments on productive forest land for all three regions per ha over the 200-year time horizon for the reference forest management scenario. NB = Norrbotten, VL = Värmland, KB = Kronoberg



Results

Reference forest carbon stocks and harvest volume developments

Figure 2 depicts simulated forest carbon stocks and harvest volume developments on productive forest land per ha of all three regions for the reference forest management scenario over a time horizon of 200 years. Overall, forest carbon stocks increase in all regions over the time horizon assessed. Across the forest growth gradient from South to North, highest overall carbon stocks and increases in standing biomass are found in Kronoberg (south), while the lowest are found in Norrbotten (north). Simulated SOC stocks initially increase slightly but remain constant over the subsequent time horizon. With growing amount of standing biomass, dead wood carbon amounts rise, however do not reach a substantial part of the overall forest carbon stocks.

Simulated harvest volumes over the time horizon of 200 years among the different regions vary more strongly compared to the forest carbon stocks and do not show continuous increase. Two dips are present after the first decade, and after 50 years which originate from the average age class distribution. On average, harvest volumes in Norrbotten were 1.5 m^3 ha^{-1} $year^{-1}$ over the considered time period, which in total constitute around one fourth of those from Kronoberg, where volumes experience a strong increase in the first six decades. Värmland shows average harvest volumes over the assessed time horizon with around 5 m^3 ha^{-1} $year^{-1}$. In Värmland, the relative harvest volume proportion comprises on average 59% sawlogs, 31% pulpwood, 9% fuelwood and 1% harvest residues. In Norrbotten and Kronoberg, relative average harvest volume proportions are 63% and 51%, 32% and 45%, 3% and 4%, and 1% and 0%, respectively.

Climate impact from a system perspective

Figure 3 shows the simulated climate impact from a system perspective for all assessed regions including the forest ecosystem and technosystem in the unit Mg CO_2-eq ha^{-1}. The results represent the relative outcome from benchmarking the alternative forest management scenarios against the reference scenario.

Overall, the higher the forest productivity, the more influential are changes in forest management on annual CO_2-eq fluxes. Among all forest management options, decreasing harvest intensity leads to cumulatively largest and continuous overall CO_2-eq emission reductions, regardless of the region but with stronger effects the more to the south, i.e. the higher the forest productivity. Considering a 25-year average this is -0.4 Mg CO_2-eq ha^{-1} $year^{-1}$ in Norrbotten, and -0.8 Mg CO_2-eq ha^{-1} $year^{-1}$ in Värmland and Kronoberg, and on a 100-year average -0.2, -0.6, and -0.7 Mg CO_2-eq ha^{-1} $year^{-1}$, respectively. Prolonging the rotation period brings a major net average CO_2-eq emission reduction within the first 25 years in all regions, (-0.7, -0.9, -1.6 Mg CO_2-eq ha^{-1} $year^{-1}$ in Norrbotten, Värmland, Kronoberg, respectively) which subsequently is partially offset by a turn into net emissions compared to the reference. This turn into net emissions originates from changes in rotation time, i.e. a changed average forest age distribution and thus timing of harvest, as compared to the reference scenario. Increasing the harvest intensity shows variable, moderate to high CO_2-eq fluxes over time in comparison to the reference. On average, however, the fluxes lead here to an increase in emissions. Shortening the rotation length has the lowest effect on the CO_2-eq balance with a minor heterogenous outcome along the time horizon.

Notably, the forest carbon sink plays the greatest role in influencing the CO_2-eq fluxes from a system perspective. Decreased forest carbon sequestration due to increased harvests is not entirely offset by substitution effects and increased HWP carbon storage. Vice versa, forgone substitution effects and omission of increased HWP carbon storage do not provoke an overall climate burden due to larger forest carbon sequestration and saved fossil value chain emissions, e.g., during scenarios of decreased harvest or increased rotation length. Across all regions and management scenarios, strong temporal variation exists in either forest carbon sequestration or harvest volumes as compared to the reference scenario. These are most pronounced in the longer rotation and increased harvest scenario.

Time dynamic temperature change

Temperature change across time including forest eco- and technosystem due to varying forest management (Fig. 4) is overall more strongly pronounced the more southern the region. The more northern, the weaker and more delayed the climate effects from altering forest management today because of slower forest growth, decomposition, etc. Regardless of the region, strongest cumulative climate cooling over a long time horizon (> 100 years) develops by decreasing harvest levels. In Kronoberg, however, extending the rotation length leads to the strongest cooling effect in the short to medium term (< 50–70 years). In Norrbotten and Värmland, in contrast, climate cooling levels from extending rotation remain overall comparable to effects from decreasing harvest levels until 75 years, and 30 years, respectively. However, afterwards, decreasing harvests induces strongest climate cooling. Shorter rotations lead to comparable effects on the temperature change as the reference scenario. Scenarios of increased harvest in contrast do not provoke additional climate cooling compared to the reference which in the short to medium term shows a heterogenous pattern and in the long term develops into a cumulative trend regardless of the region.

Sensitivity analysis

Figure 5 shows the temperature change impacts of all forest management alternatives until 2070 for an increased $DF_m = 1.4$ or reduced $DF_m = 0.2$, due to doubling or halving all replacement rates of all HWP end-uses. Each scenario equals the respective average from all regions under study as compared to the reference.

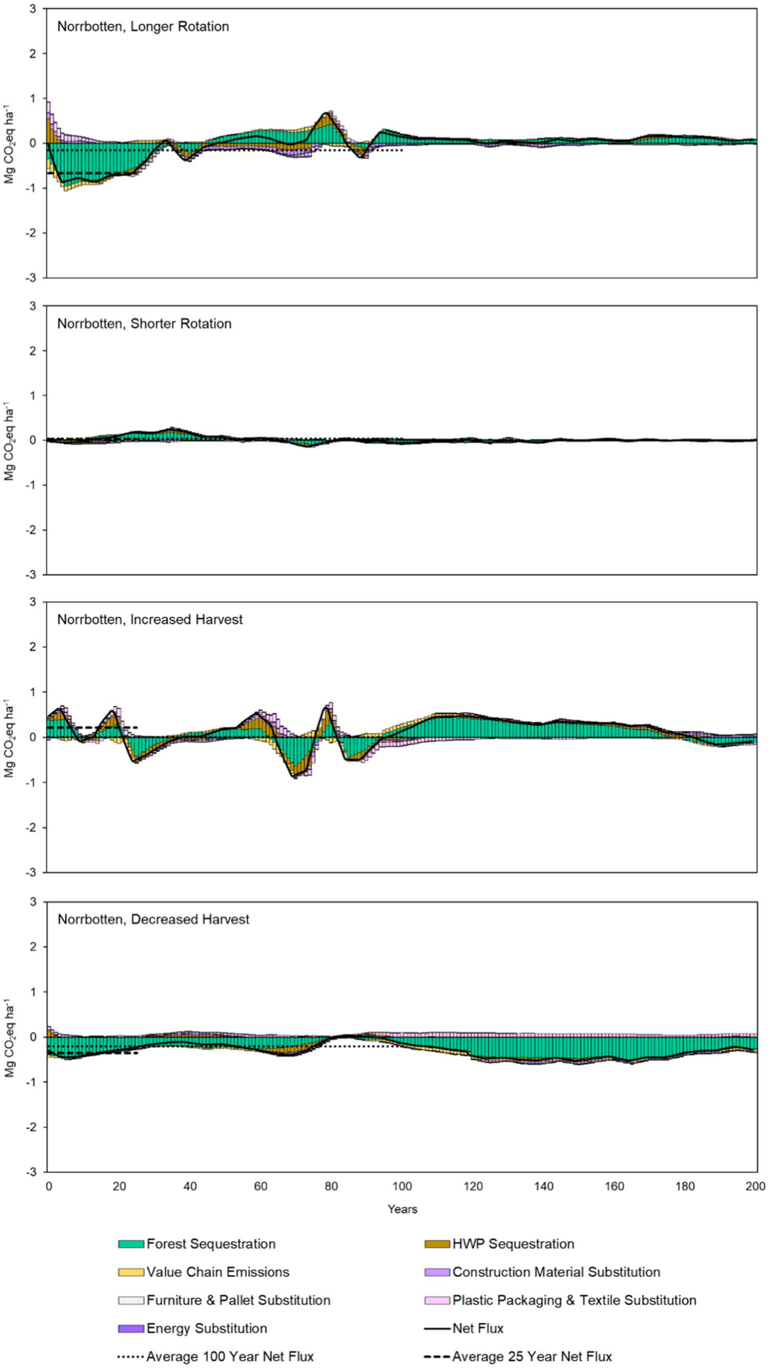


Fig. 3 Annual climate impact (Mg CO_2-eq ha^{-1}) from all forest management scenarios in Norrbotten, Värmland, and Kronoberg over the 200-year time horizon as compared to the reference. Positive values represent emissions to the atmosphere. HWP = Harvested Wood Product

Fig. 3 (continued)

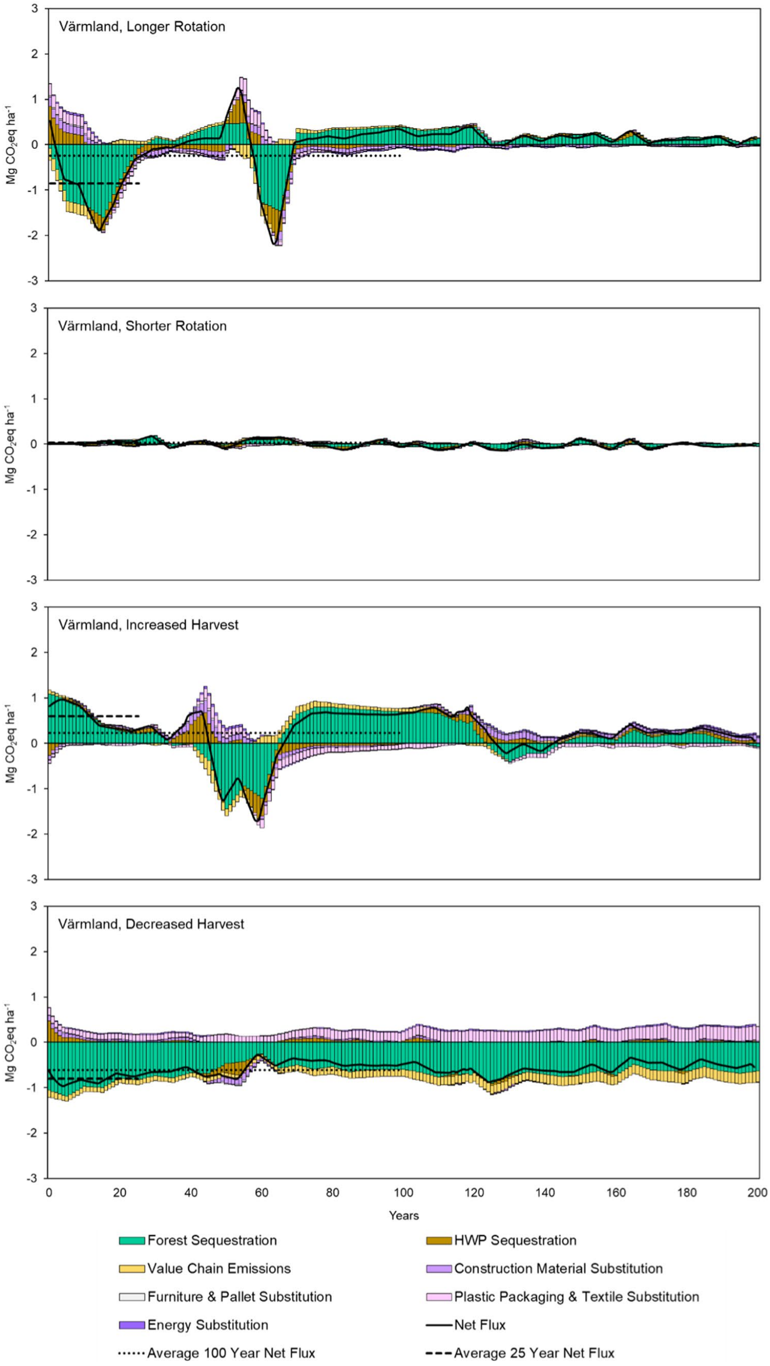
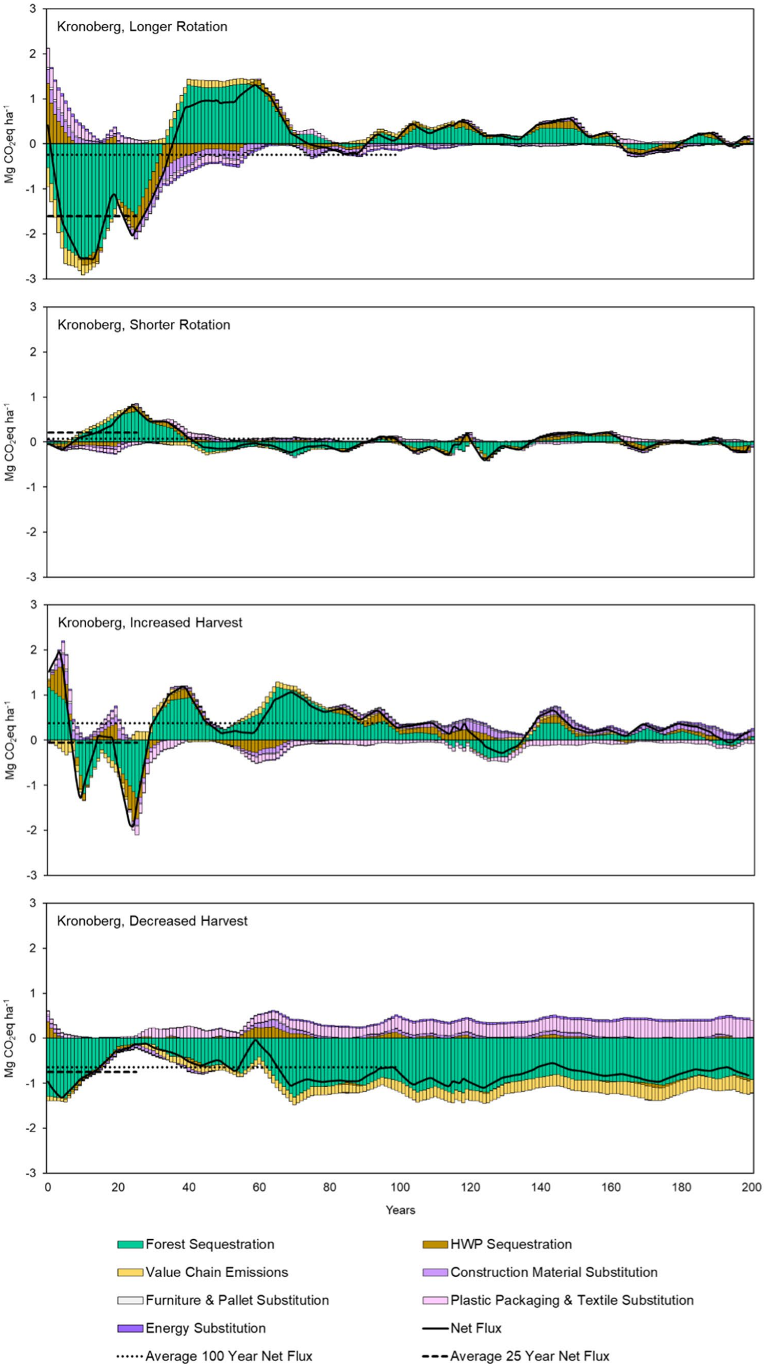


Fig. 3 (continued)



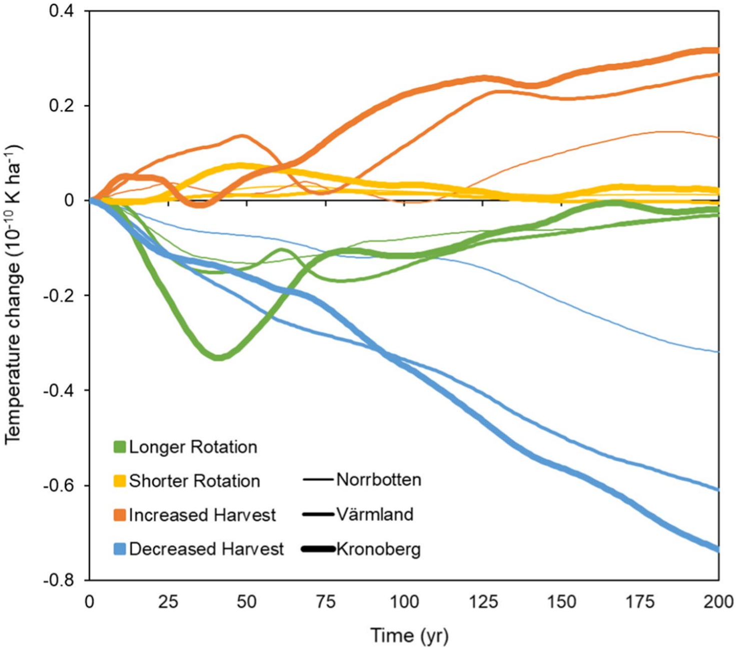


Fig. 4 Temperature change per ha given for all forest management scenarios and regions under study as compared to the reference scenario

An altered DF_m does not change overall temperature change from net cooling towards net warming except during the first decade of the longer rotation scenario. However, in all scenarios apart from shortening the rotation, a higher DF_m leads to decreased cooling effects. For prolonging the rotation and decreasing harvest levels, this is due to larger forgone substitution effects. In the increased harvest scenario, a higher DF_m induces increased climate warming as the temporal variation of surplus and decrease in harvest volumes compared to the reference scenario causes an overall net forgone substitution effect.

Discussion

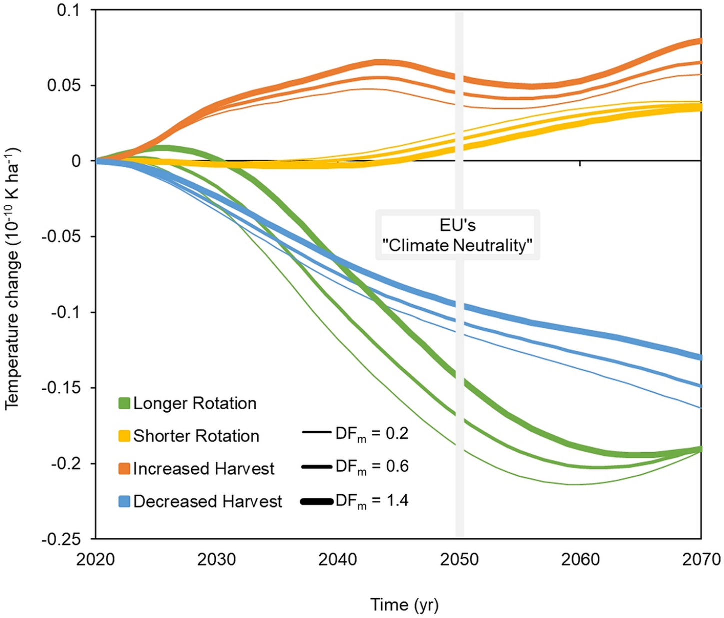
The Nordic forest sector climate change mitigation trade-off

Despite numerous studies applying a system perspective in analysing climate effects of forest management including substitution effects, the scientific debate on the most effective climate strategy is still not settled.

The results of the present study complement and align with an international body of knowledge indicating that alternative forest management with decreased harvests and increased forest carbon sequestration benchmarked against current reference levels leads to larger net climate benefits (Matsumoto et al. 2016; Skytt et al. 2021; Seppälä et al. 2019; Jonsson et al. 2021; Soimakallio et al. 2021; Biber et al. 2020; Dugan et al. 2018; Hurmekoski et al. 2020) opposed to increasing harvest levels to exploit substitution effects (Gustavsson et al. 2021; Petersson et al. 2021). In fact, across all studied regions, an average additional mitigation potential of – 1.0 Mg CO_2-eq ha^{-1} was found over the next 25 years when rotations are prolonged, and – 0.7 Mg CO_2-eq ha^{-1} when harvest levels are decreased. This represents additional climate cooling until 2050 of – $0.16 \cdot 10^{-10}$ K ha^{-1} for prolonging rotations, and – $0.10 \cdot 10^{-10}$ K ha^{-1} for decreasing harvest levels.

However, within the Swedish context, it must be recognized that strong forest carbon sinks following prolonged rotations or decreased harvests are, at least partially, a consequence of the present age class distribution (Supplementary Material) characterized by numerous young stands and strong forest growth. This baseline is shaped by decades of active forest management in Sweden, limiting superior climate benefits to several decades, as prolonged rotations may compromise additionality to other scenarios (Lundmark et al. 2018).

Fig. 5 Temperature change as an average across all regions given per ha for all forest management scenarios when compared to the reference scenario in dependence to a varying market displacement factor (DF_m)



Unless harvest volumes are not used more wisely with considerably larger shares of long-lived wood products (Dugan et al. 2018; Arehart et al. 2021), carbon emissions from bioenergy production are not captured and stored (BECCS), or wood products do not lead to substantially higher substitution effects, for example, by an increasing demand for wood-based housing, a superior climate benefit may originate from a large forest sink (Soimakallio et al. 2021). Furthermore, decreasing harvests and prolonging rotations can provide a higher ratio of sawlogs to pulpwood, resulting in more long-lived products, in a relative sense, as deducible in the decreased harvest scenario across all regions, where mostly pulpwood-based substitution effects are forgone. On the other hand, decreased harvests can result in reduced silvicultural activity as well as decreased economic profitability (Baul et al. 2017), as Swedish forestry today largely relies on wood production (Hiltunen et al. 2021). Thus, climate change mitigation trade-offs among forest management strategies have socio-economic implications, influencing future job opportunities throughout the next decades (Jonsson et al. 2021).

In terms of shortened rotations, the smallest change from the reference scenario and no long-term overall climate benefit was found. However, shorter rotations bear potential to avoid severe forest carbon loss from calamities such as storms (Subramanian et al. 2019) despite being considered to compromise overall forest resilience due to negative consequences for other ecosystem services and biodiversity (Ortiz et al. 2014; Egnell et al. 2015; Felton et al. 2016).

Climate relevance of additional forest management alternatives

Rotation forestry bears additional options for improving climate change mitigation and adaptation. Among them are, increased harvest residue extraction considering biodiversity constraints (Eggers et al. 2020; Camia et al. 2021), retention forestry (Cherubini et al. 2018), or diversifying species composition (Hahn et al. 2021).

Transformation into continuous cover forestry (CCF) is further perceived a promising strategy for improved climate change mitigation and adaptation (Pukkala 2014) for increased forest multifunctionality opposed to rotation forestry (Eyvindson et al. 2021), and thus a more balanced fulfilment of forest policy goals (Eggers et al. 2019) while not constraining forest carbon sequestration (Biber et al. 2020).

No forest management including natural regeneration can be another short- to medium-term climate change mitigation and adaptation strategy to foster forest carbon sequestration and simultaneously increase genetic variation within tree species (Soimakallio et al. 2021), yet it is uncertain regarding long-term climate effects (Knauf et al. 2015; Skytt et al. 2021).

Still, more climate-smart Nordic forest landscapes require mosaics of varying forests including even-, uneven-aged, and natural forests comprising multi-layered mixed stands (Savilaakso et al. 2021; Eyvindson et al. 2021; Soimakallio et al. 2021). Change across all of Europe is urgent given projected climate change and connected economic losses of forests at the end of the century, in the absence of effective counteraction (Hanewinkel et al. 2013). Actual implementation, however, always requires consideration of regional circumstances.

Methodological limitations in wood product climate assessments

Recommended methodological approaches in assessing climate effects from wood product systems across time cover biogenic carbon, valid counterfactual scenarios (Giuntoli et al. 2020), or, examining both, short and long time horizons (Gustavsson et al. 2021). However, additional aspects still leave considerable space for uncertainty.

One is reliance on forest models to process empirical NFI data. In this study, the Heureka RegWise software was applied whose growth models were shown to be reliable within even-aged forest management along extended time periods (Fahlvik et al. 2014). Although available, the climate model and storm model inherent to Heureka were excluded as both insufficiently represent probable climate change-induced developments (Subramanian et al. 2019).

However, Nordic forest growth is expected to increase substantially as a result of climate change (Claesson et al. 2015; Subramanian et al. 2019), at the same time as forest calamities (bark beetle outbreaks, storm events, fires) and biomass decomposition are foreseen to increase in frequency and magnitude, thereby potentially offsetting climate benefits from increased forest growth (Kauppi et al. 2018; Subramanian et al. 2019) as, for example, shown in a Finnish case by Reyer et al. (2017). By omitting these aspects in the assessment, the present study thus can be seen to provide more conservative results as both potentially beneficial (i.e. forest growth-enhancing) and detrimental (i.e. mortality exacerbating) factors were neglected in the model and including these (simplistic) modelling features would add considerable uncertainty.

Wood flow models based on LCA data are likewise subject to assumptions influencing the outcome from forest management scenarios. Among them are fixed vs. dynamic annual harvest volumes and wood product portfolios across time (Hurmekoski et al. 2020; Brunet-Navarro et al. 2021), only approximate half-life times using exponential decay functions for HWPs (Hurmekoski et al. 2020; Brunet-Navarro et al. 2021) improvable, e.g., by gamma decay functions, missing albedo as a climate forcer despite its globally inferior role than CO_2 effects (Pongratz et al. 2010; Cherubini et al. 2018; Kalliokoski et al. 2020), or accounting for indirect land-use changes (Howard et al. 2021). Finally, increased knowledge on consequential modelling of wood product systems relying on LCA data (Helin et al. 2013; Cordier et al. 2021) and a more uniform and nuanced assessment approach for substitution effects are required.

Uncertainties connected to substitution effects

Substitution effects remain a highly uncertain and influential factor in climate assessments of wood products for which until today no universal way of conduct exists. Still, the commonly applied substitution or displacement factor (DF) (Sathre and O'Connor 2010) can be a metric to express the magnitude of avoided fossil C per unit of biogenic C in the wood product. The weighted average displacement factor or market displacement factor (Hurmekoski et al. 2021) found in this study was $DF_m = 0.6$ Mg C Mg C^{-1} and is thus in line with comparable national studies in Nordic contexts such as Lundmark et al. (2014) for Sweden (0.6 Mg C Mg C^{-1}), Soimakallio et al. (2016) for Finland (0.4–0.8 Mg C Mg C^{-1}), or Smyth et al. (2017) for Canada (0.5 Mg C Mg C^{-1}). Further, the value coincides with the average DF_m of the review from Hurmekoski et al. (2021) (0.55 Mg C Mg C^{-1}), which, however, still shows great interval to a required DF_m (2.0–2.4 Mg C Mg C^{-1}) which would mark net zero emissions from increased forest use compared with a baseline harvesting scenario (Seppälä et al. 2019).

However, as summarized by Howard et al. (2021), several assumptions manipulate substitution effects of wood products that impede comparisons of DFs among studies. Spatial assumptions such as equal HWP production with similar energy demands across regions considering changed harvest rates (Smyth et al. 2017), neglection of market and legislative aspects, such as international trade and employment effects from increased wood product consumption (Jonsson et al. 2021) or the emissions trading system of the EU further increase uncertainty.

Since assumptions on substitution effects lacking real-life complexities can result in too optimistic DFs, former conclusions of DFs and substitution effects were regarded to be strongly overestimated (Leturcq 2020; Harmon 2019). In contrast are future substitution effects of wood products considered to decrease, e.g., due to required political climate targets (Brunet-Navarro et al. 2021) and associated decarbonisation of other industrial sectors (Arehart et al. 2021). Climate policy advice solely based on displacement factors bears therefore too much uncertainty to provide reliable consultation (Leskinen et al. 2018; Hurmekoski et al. 2020).

Thus, further studies such as the present one which supply more detailed, time dynamic breakdowns of substitution effects, especially following shifts in forest management, are required, that specify pulpwood, fuelwood, or sawlog-based substitution. In addition, development of dynamic displacement factors is recommended to account for above-mentioned shortcomings, e.g., with accounting for political climate targets by assuming an expected increase in renewable energy in line with the Paris agreement (Brunet-Navarro et al. 2021).

Conclusion

The results of the present study suggest that decreasing harvest levels and prolonging rotations would increase net climate benefits compared to present Swedish forestry practices. Across all three regions assessed, prolonging rotations by 20% leads on average to additional climate benefits of -1.0 Mg CO_2-eq ha^{-1} over the next 25 years, while decreasing harvests accordingly induces -0.7 Mg CO_2-eq ha^{-1}. This equals additional temperature cooling effects of $-0.16 \cdot 10^{-10}$ K ha^{-1} until 2050 for prolonging rotations, and $-0.10 \cdot 10^{-10}$ K ha^{-1} for decreasing harvest levels.

However, forest calamities induced by climate change are likely to somewhat compromise these potential additional climate cooling effects, in which case shorter rotations and increased harvests provide more resilient management approaches. Despite this, resilient long-term climate change mitigation and adaptation strategies for Swedish forests may still be found in increasing more heterogenous forest landscapes. These could include longer rotations, reduced harvests, and changing tree species to those more apt for local site conditions. The transformation of some of the forest area to CCF could be a promising strategy for increased forest multifunctionality, while at the same time not constraining forest carbon sequestration. This transformation still requires considerations of local circumstances. As for policy advice, remaining knowledge gaps and uncertainties—notably, the magnitude and local effects of climate change, substitution effects, carbon leakage effects, and long-term forest growth dynamics given climate change—hinder the formulation of concrete, precise, suggestions. However, the need for changing Swedish forest management is urgent given projections of future climate change and associated ecological, societal, and economic value loss of forests across Europe at the end of the century in the absence of effective countermeasures.

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Author contributions Maximilian Schulte was involved in conceptualization, methodology, formal analysis, writing—original draft, visualization. Ragnar Jonsson contributed to conceptualization, validation, writing—review and editing. Torun Hammar was involved in conceptualization, methodology, resources, writing—review and editing. Johan Stendahl contributed to conceptualization, validation, resources, writing—review and editing. Per-Anders Hansson was involved in conceptualization, supervision, project administration, funding acquisition.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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Demand-driven climate change mitigation and trade-offs from wood product substitution: The case of Swedish multi-family housing construction

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ABSTRACT

Multi-family housing construction (MFHC) with wood instead of concrete as frame material results in lower greenhouse gas emissions. Hence, substituting wood for concrete in MFHC in Sweden until 2030, and onwards to 2070, could be a promising climate change mitigation option. But to what extent, and how would it impact Sweden's forests? Here we assess climate and biodiversity implications - in terms of the area of old forest - of a completely wood-based future MFHC in Sweden. The wood required is assumed to be exclusively sourced as additional fellings in Swedish forests, thus carbon leakage from wood imports as well as displacement of other wood uses can be disregarded. Different types of timber frame systems and the role of varying future dwelling sizes are considered. We find that the wood needed for a complete substitution of concrete would result in very minor increases in harvests. We further register slight net additional climate change mitigation, irrespective of the wood construction system. There is a small tradeoff between climate change mitigation and biodiversity, as the area of old forest reduces slightly. The largest climate benefit, and lowest impact on Swedish forests, is provided when using timber-light frame combined with reduced dwelling size.

1. Introduction

Building materials and construction account for twenty percent of annual global carbon dioxide (CO_2) emissions (UNEP, 2022). The use of wood products in construction meanwhile appears to have one of the largest climate change mitigation potentials (Sathre and O'Connor, 2010; Leskinen et al., 2018; Myllyviita et al., 2021). Strong evidence thus indicates climate superiority of wood frame over concrete- and steel frame buildings (Gustavsson et al. 2017, 2021; Head et al., 2020; Andersen et al., 2022; Peñaloza et al., 2016; Chen et al., 2020; Cordier et al., 2021; Piccardo and Gustavsson, 2021; Himes and Busby, 2020; Mishra et al., 2022). Accordingly, the new EU forest strategy (EC, 2021a) maintains that the most important role of wood products is to help turn the construction sector from a source of greenhouse gas emissions into a carbon sink, as set out in the New European Bauhaus initiative (EC, 2021b). Indeed, there are numerous other national, and international initiatives and policy programs promoting the application of wood in construction for climate change mitigation and restoration, e.g., Built by Nature (Built by Nature, 2022), or Bauhaus Earth (Bauhaus Earth, 2022).

A relevant feature influencing the overall environmental burden of housing, regardless the material type, is the dwelling size per capita, e.g., in terms of energy consumption (Ivanova and Büchs, 2022). Throughout the past decades however, the average dwelling size per capita kept on increasing globally (Ellsworth-Krebs, 2020) although shrinking the dwelling area would lead to a generally decreased environmental impact. This highlights large potentials for downsizing or shared living in future design and construction of housing (Huebner and Shipworth, 2017; Ivanova and Büchs, 2022) irrespective of the materials applied.

Sweden is amongst the forerunners in the EU when it comes to wood-based construction (Trinomics et al., 2021). Timber frame (used synonymously with wood frame) dominates in the construction of

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List of Abbreviations

AGTP	Absolute global temperature change potential
ATF	Average timber frame
CLT	Cross-laminated timber
EU	European Union
EWP	Engineered wood product
DF	Displacement factor
HWP	Harvested wood product
GHG	Greenhouse gas
GLT	Glued-laminated timber
GWP	Global warming potential
LCI	Life cycle inventory
MFH	Multifamily-housing
MFHC	Multifamily-housing construction
RCP	Representative concentration pathway
SOC	Soil organic carbon
TLF	Timber light frame

single-family housing, with a market share of around 90% (Swedish Wood, 2023), while concrete still dominates as frame material in multi-family housing construction (MFHC), accounting for 80% during 2019–2020 (SCB, 2022a; SCB, 2022b). However, timber frame, with a share of 19% during 2019–2020 (Malmqvist et al., 2021; SCB, 2022a), has increased significantly in MFHC in absolute terms following changes in the building code in 1994, allowing timber frames in buildings with more than two storeys (Bengtson, 2003). Moreover, the use of timber frame in MFHC has been furthered by the introduction of engineered wood products (EWPs), such as cross-laminated timber (CLT) and glued-laminated timber (GLT). Hence, EWPs have enabled the construction of functionally equivalent wood-based buildings in terms of safety and technical requirements (Gustavsson et al., 2021; Andersen et al., 2022). In addition, consumers positively associate timber frame housing with environmental and social sustainability aspects which enables for increased opportunities to capture market advantages (Roos et al., 2022).

To meet expected demographic trends, 600,000 new dwellings need to be built until 2030 in Sweden (Boverket, 2021; SCB, 2022a), chiefly in multi-family housing (MFH) given its dominance in residential construction, making up 77% of recently built dwellings (SCB, 2022a). Thus, there is a considerable potential for timber frame to substitute for concrete frame in MFHC. Accordingly, we intend to explore implications in terms of climate change mitigation potentials and the future state of Swedish forests of a complete substitution of concrete by timber in MFHC from 2030 and onwards in Sweden. Sourcing the wood needed exclusively through increased domestic fellings implies that other uses of wood are not displaced.

In terms of a system perspective of the forest sector (EC, 2021a), a common – in Sweden hitherto dominant – approach when assessing climate change mitigation potentials of forest management and the associated wood use is that of a supply-perspective, "from-the-forest-to-the-wood-use". Substitution effects are estimated for the harvested wood products (HWPs) that result from annual harvest volumes, often by using substitution, or displacement factors (DFs) on product (Sathre and O'Connor, 2010), or market level (Hurmekoski et al., 2021).

Hence, the supply-perspective credits HWPs with avoidance of greenhouse gas (GHG) emissions, i.e. substitution effects, merely due to their supply and without accounting for the demand. The overriding premise is that an increase in production of the wood-based commodity in question results in an equal increase in total consumption thereof, which amounts to an (implicit) assumption of perfectly elastic demand (Mas-Colell et al., 1995). Indeed, a major shortcoming of many studies is that critical assumptions applied, such as the issue of market effects leakage (Aukland et al., 2003) are rarely explicitly stated and addressed (Schweinle et al., 2018; Harmon, 2019; Jonsson et al., 2021; Hurmekoski et al., 2022). As a result, wood product substitution effects are often overestimated (Leturcq, 2020). This as substitution is only effective as far as (i) an increase in the supply of a wood product in a certain region results in an equal increase in the Global consumption of this wood product (i.e., there is no market effects leakage), in turn leading to (ii) a Globally verifiable reduction in non-wood products. Otherwise the manufacture of the wood product merely adds to overall supply (Hurmekoski et al., 2022) and thus results in net additions of GHG emissions.

In order to address this inconsistency, a demand-perspective for modelling climate change mitigation potentials of wood use can be applied. In contrast to the former, this perspective follows "from-the-wood-use-to-the-forest" and is targeted to a specific HWP application, e.g., construction. Adopting the United Nations Framework Convention on Climate Change's (UNFCCC) view on mitigation (UNFCCC, 2022), the substitution effect here is stated as a relative concept, i.e., absolute avoided emissions in alternative scenarios that deviate from a reference or baseline scenario, leaving the estimation of a DF an optional feature (Hurmekoski et al., 2021). The alternative scenarios and the reference are characterized by differing amounts of HWPs and substituted alternatives. GHG balances on the product level rely on life cycle inventory (LCI) data. This assessment approach was, e.g., applied by Hafner and Rüter (2018) to investigate the climate benefit of increased residential wood-based buildings in Germany based on national projections.

We apply a demand-perspective in analyzing the climate change mitigation potential at national level of an increased use of wood-based MFHC in Sweden. This is done by integrating LCI data at the building level, Swedish residential housing statistics, projected housing demand, and demographic projections. This approach avoids the assumption of a perfectly elastic demand in wood-based markets and circumvents estimating the share of different end-uses in the consumption of semi-finished wood products in question, as necessary when applying the supply-perspective.

As such, the study assesses climate and biodiversity implications of an entirely wood-based future Swedish MFHC, when the wood required is sourced from Swedish forests, and thereby not induces imports or displaces other wood uses. Climate impacts are estimated within the short (<20 years) to medium term (<50 years). Biodiversity impacts of ensuing increased harvests of roundwood are assessed using the indicator of old forest area, (Sveriges Miljömål, 2023; Swedish University of Agricultural, 2023). We ascertain which type of wood-based construction system and associated wood-use intensity would result in the largest climate benefit and consider the role of future dwelling sizes in MFHC for climate change mitigation. The outcomes are, in addition to GHG emissions, assessed in terms of time dynamic temperature change as to when and to which extent potential climate change mitigation occurs.

2. Materials & methods

2.1. System boundaries

Fig. 1 shows the system boundary of the study which is geographically limited to Sweden. The modelling starts with the projected demand for MFHC in Sweden and scenarios (Section 2.2). This demand can be met by two dwelling alternatives: a concrete frame, or a wood frame dwelling each of which requires certain types and amounts of materials. Thus, two representative dwelling equivalents are defined and their construction is upscaled to the national level (Section 2.3). In order to account for the climate effects due to changes in the relative share of the dwelling equivalents, a technosystem as well as a forest system are defined where the supply of all materials used for the dwelling alternatives are backtracked from the wood end-use application to the origin ("cradle") (Section 2.4). Within the technosystem some parts are "cut-off" the system boundary, notably downstream use of some sawmill by-products, upstream logging residues and pulpwood use. A crucial ceteris

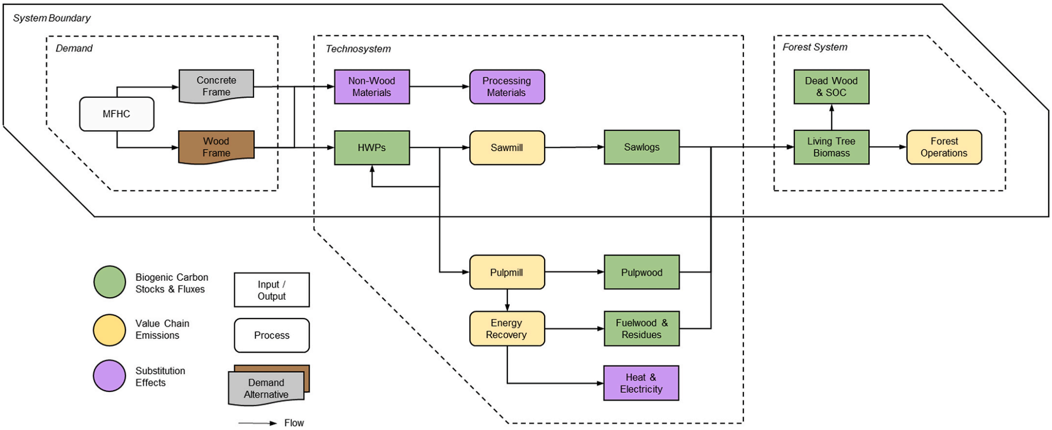

Fig. 1. System boundary starting from the demand of additional multi-family housing construction (MFHC) met either by concrete frame or wood frame, and continuing over implications within the technosystem, and the forest system. Note that parts of the technosystem are “cut-off” from the system boundary, and that only MFHC-related by-product-based HWPs from sawmill activity are included (particleboard), but other HWPs made from sawmilling by-products (e.g., furniture use) are excluded. HWP: harvested wood product.

paribus assumption is thus that the wood used for additional increases in wood-based construction is entirely sourced from additional fellings in productive Swedish forests only, while not impacting other wood uses and associated non-wood product value chains. We focus here on the required additional dwellings and increasing wood share in MFHC only. This, as single-family houses only account for the minority of recently built dwelling types (23%), and wood frame here is already dominating the market as load-bearing structure with a share of around 90% (Swedish Wood, 2023). Given the multitude of different dwelling sizes and forms in MFHC, the functional unit during the calculations was adapted to a square meter (m^2) of living area.

2.2. Multifamily-housing demand, future reference projection and scenarios

Fig. 2 presents annual historical MFHC by type of frame material for Sweden from 1995 until 2020, and a reference projection as well as two scenarios all ranging from 2021 until 2030 and reaching 2070, based on (SCB, 2022a, 2022b; Boverket, 2021). In the past, from 1995 until 2020, concrete frame was the dominating construction type, on average with an 87% share while wood frame gained an increasing application share over time, accounting, on average, for about 13% throughout 1995–2020, and increasing to around 19% during 2019–2020.

In the future, we assumed that both, the reference projection, and the scenarios meet the expected housing demand of 461,000 additional dwelling units in MFH by 2030, according to the average MFHC market share of 77% from the past five years. In total that is a MFHC increment of 3.1% per annum until 2030. Past 2030 until 2070, both, reference projection and scenarios are assumed including an average MFHC increment of 0.4% in accordance with projected demographic developments in Sweden (SCB, 2022c).

In the reference projection the relative share among concrete frame and wood frame in a growing MFHC market until 2070 is set conservatively and maintains today’s proportion of 81% concrete frame and 19% wood frame. In contrast, the two scenarios increase the wood frame share by 18.1% per annum as compared to the reference projection from 19% in 2020 to 100% in 2030 and keep it stable on this level until 2070. The first scenario, “Average Timber frame”, in the following referred to with “ATF” scenario, maintains the Swedish market shares of the three current wood frame types and thus equals a weighted average of timber

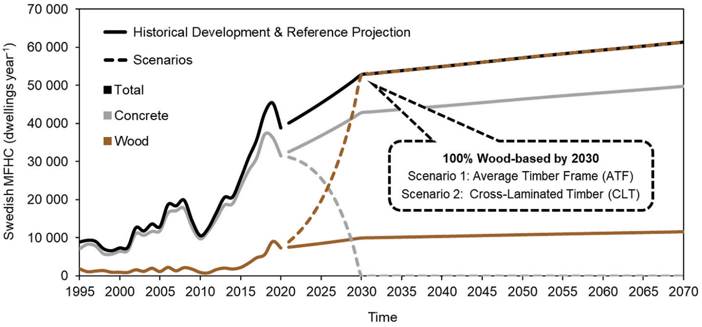

Fig. 2. Annual historical Swedish MFHC (1995–2020) (SCB, 2022a, 2022b), reference projection, and scenarios (2021–2070), given per frame material used. MFHC = Multi-family housing construction.

light-frame constituting 85% (Rudenstam 2021), and, in absence of information, assumptive 7.5% market shares of cross-laminated timber and glued-laminated timber, respectively. The second scenario, “Cross-Laminated Timber”, in the following referred to as “CLT” scenario, accounts for gradual decreases in the timber light-frame and glued-laminated timber shares. The scenario assumes that by 2030, 100% of additional wood-based dwellings are made out of cross-laminated timber which then keeps constant until 2070. Table 1 summarizes the reference projection and scenario assumptions. To varying degrees, both scenarios thus entail an additional demand of HWPs and thus outtake of roundwood from Swedish forests, which is benchmarked against the counterfactual reference projection that foresees a continuation of underlying trends in the demand and provision of wood products. Note that the residual frame types apart from concrete frame and wood frame, such as steel, were excluded from the analysis due to negligible market shares.

2.3. Dwelling equivalents and upscaling procedure to the national level

To reasonably determine and compare wood frame and concrete frame MFHC alternatives, and their future projections in terms of their climate performance, functionally equivalent dwelling archetypes are required. However, types and amounts of resources applied in both dwelling alternatives can differ substantially, which necessitates an approximation thereof as presented in Table 2 per m^2 in the functionally equivalent wood frame and concrete frame dwelling archetypes. For this, the material inventory from Gustavsson et al. (2017) was used as the basis for modelling, as it enables to represent an average wood frame dwelling that allows accounting for timber light frame, cross-laminated timber, and glued-laminated timber market shares. These three wood frame types, and the concrete frame alternative, are functionally equivalent building archetypes characterized by the same energy use and building service covering a lifetime of 80 years. In this instance, the carbonation process of the concrete applied was disregarded as it is considered not to generally alter climate results from comparisons of wood frame and concrete frame buildings, see, e.g., Dodoo et al. (2009). The amount of total air-dry wood use per living area in the weighted average timber frame dwelling is 89 kg m^{-2} (ATF scenario) and in the cross-laminated timber dwelling 109 kg m^{-2} (CLT scenario). In the concrete frame alternative it amounts to 66 kg m^{-2}. See the Supplementary Material for more detailed information.

The production related fossil GHG emissions of all wood frame and the concrete frame dwelling equivalents were deduced using LCI data from the Ecoinvent 3.8 database (Wernet et al., 2016). Here, the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were inventoried for all resources applied, except for rubber and crushed stones, whose emissions are negligible (Supplementary Material). Table 3 summarizes these fossil value chain emissions in form of the global warming potential (GWP_{100}) in the unit of Mg CO_2 equivalents (Mg CO_2 eq). A square meter living area of the concrete frame dwelling amounts to 0.25 Mg CO_2 eq, while both, the weighted average timber frame alternative (ATF scenario) and the cross-laminated timber dwelling (CLT scenario) constitute 0.11 Mg CO_2 eq. Upscaled to the dwelling level, this amounts to 14.2 Mg CO_2 eq of fossil value chain emissions for the concrete frame, 6.3 Mg CO_2 eq per weighted average timber frame alternative (ATF scenario), and 6.1 Mg CO_2 eq per cross-laminated timber dwelling, considering an average Swedish dwelling size of 57 m^2 (SCB, 2016).

Table 1
Swedish MFHC reference projection and scenario properties from 2021 to 2030, and 2031 to 2070. MFHC = Multi-family housing construction; TLF = timber light frame; CLT = cross-laminated timber; GLT = glued-laminated timber. See the Supplementary Material for more detailed information.

Property	Reference Projection	Scenario 1: ATF	Scenario 2: CLT
Annual MFHC increment during 2021–2030 and 2031–2070, respectively	3.1% 0.4%	3.1% 0.4%	3.1% 0.4%
Annual wood frame MFHC increment during 2021–2030 and 2031–2070, respectively	0% 0%	18.1% 0%	18.1% 0%
Relative distribution of wood frame MFHC after 2030	85% TLF 7.5% CLT 7.5% GLT	85% TLF 7.5% CLT 7.5% GLT	0% TLF 100% CLT 0% GLT

Table 2
Type and amounts of required materials of the concrete frame, average timber frame and cross-laminated timber dwelling equivalent given in kg m^{-2} living area, based on Gustavsson et al. (2017). The average timber frame dwelling comprises 85% timber light frame, 7.5% glued-laminated timber frame, and 7.5% cross-laminated timber frame, respectively.

Material	Concrete Frame Dwelling	Average Timber Frame Dwelling	Cross-Laminated Timber Frame Dwelling
Concrete	1138.6	100.6	96.6
Steel	21.4	3.6	4.4
Aluminum	0.0	0.5	0.5
Mortar	19.6	9.8	14.9
Stone-Wool Insulation	11.1	2.1	13.6
Glass-Wool Insulation	1.3	10.9	0.0
Plasterboard	21.2	85.7	60.8
Polyvinylchloride	1.6	0.6	0.6
Polyurethane	0.0	4.2	3.4
Expanded Polystyrene	2.4	2.4	2.4
Crushed Stone	267.0	265.0	265.0
Lumber (Sawnwood)	34.7	43.5	36.3
Cross-Laminated Timber (CLT)	0.0	7.2	46.0
Laminated Veneer Lumber (LVL)	0.0	3.8	0.0
Glued-Laminated Timber (GLT)	0.0	8.7	17.0
Particleboard	14.6	15.1	3.3
Plywood	16.7	6.9	5.6
Laminated Wood Flooring	0.0	3.8	0.5
Wood Use	66.1	89.1	108.7

Table 3
Fossil GHG profiles of concrete frame, average timber frame (ATF scenario) and cross-laminated timber frame (CLT scenario), given per dwelling unit (average size of 57 m^2) and m^2 living area, expressed in Mg CO_2 eq.

Level	Unit	Concrete Frame	Average Timber Frame	Cross-Laminated Timber Frame
Dwelling Unit	Mg CO_2 eq	14.17	6.28	6.11
Square meter living area	Mg CO_2 eq	0.25	0.11	0.11

The subsequent upscaling from the dwelling to the national level was done by linking the fossil GHG emission profiles at the dwelling level with the reference projection and scenarios as defined in Section 2.2. The relative demand differences of wood-based construction between the reference projection and the scenarios thus induced relative changes in fossil GHG emissions (substitution effects), and in biogenic carbon balances in HWPs and the originating Swedish forest. Consequently, the definition of a reference wood product technosystem and forest system is required.

2.4. Techno- and forest system

2.4.1. Technosystem

Within the technosystem, additional HWP carbon storage and the fossil GHG emissions per additionally built dwelling equivalents as defined in Section 2.3 were accounted for. To receive the relative change of the HWP carbon storage pool, the conversion from the additionally demanded HWP amount per dwelling was performed to the amount of roundwood increments of sawlogs.

Retracing the increased sawlog processing in sawmills was identified by backtracking the additional net HWP amount given in kg HWP m^{-2} of dwelling area to the originating additional sawlog harvest in m^3 (under bark) which was required to meet the additional demand. For this, each HWP amount given in kg HWP m^{-2} was first converted into its volume, i.e., m^3 HWP m^{-2}, using conversion factors for Swedish conditions (FAO, 2020). In a second step the volume of each HWP per square meter, i.e., m^3 HWP m^{-2}, was converted into the volume of roundwood equivalents, i.e., m^3 roundwood under bark m^{-2} (Mantau, 2010), corresponding to each HWP in use, including cross-laminated timber and glued-laminated timber (Werner, 2022a, 2022b). Accordingly, the weighted average timber frame dwelling (ATF scenario) uses 0.19 m^3 m^{-2}, and the cross-laminated timber equivalent (CLT scenario) uses 0.24 m^3 m^{-2}. However, considering the density of the different HWPs applied and the conversion rate from carbon to CO_2 of 3.67, the retained biogenic carbon amount in HWPs amounted to 879 kg CO_2 eq m^{-3} for the weighted average timber frame dwelling (ATF scenario), and to 843 kg CO_2 eq m^{-3} for the cross-laminated timber dwelling (CLT scenario). See the Supplementary Material for details.

The increased demand of wood-based construction in the scenarios steered the additional sawlog processing and roundwood harvest volume. The net additional sawlog processing and roundwood harvest volume equals the difference between the saved sawlogs from the substituted concrete frame dwellings, and the increased requirement for sawlogs for the wood frame dwellings. As this could potentially impact other uses of wood, notably those using side-streams originating from sawmill activity, and their preceding inputs (pulpwood, fuelwood, and residues), as well as succeeding outputs (substitution effects from pulpwood products and energy recovery), these were "cut-off" from the system boundaries for simplification reasons, as stated under Section 2.1. Further we assumed that particleboard manufacturing in the scenarios was entirely based on sawmilling by-products (sawmilling by-products and pulp logs are perfect substitutes in this context), which is reasonable given the abundance of sawmilling by-products. The leftover amount not used for particleboard production, i.e., the "surplus" of by-products were "cut-off" the system boundaries. See the Supplementary Material for more information.

For the HWP carbon storage accounting, half-life times of 35, and 25 years were applied for sawnwood-based (lumber, CLT, glulam), and panel- or board-based (laminated veneer lumber, particleboard, plywood, laminated wood flooring) products, respectively (Rüter et al., 2019).

2.4.2. *Forest system*

In accordance with the demand-perspective stated above "from the end-use to the forest", the net annual roundwood harvest volumes of sawlogs were used as input in the forest decision support system Heureka PlanWise (Wikström et al., 2011) to simulate the relative implications on the forest carbon pool. In parallel, Heureka PlanWise served as the modelling tool to define the reference forest system, comprising biogenic carbon stocks from living tree biomass, soil organic carbon (SOC), and dead wood, as well as the reference national harvest levels. For the latter, the business-as-usual scenario of SKA 22 (the official Swedish forest impact analysis) was applied (Eriksson et al., 2022).

The forest system was geographically set to the productive forest land in Sweden and based on the National Forest Inventory (NFI) data from 2020. The productive forest land ($\geq$1 m^3 growth ha^{-1} $year^{-1}$) amounts to around 24,000,000 ha and excludes non-productive forest-land (<1 m^3 growth ha^{-1} $year^{-1}$) equalling around 4,300,000 ha. On productive forest land, voluntarily and formally set-aside areas were excluded for the analysis. The mean wood volume on productive forest land equals 139 m^3 ha^{-1}, excluding the nature reserves and set-aside lands, and the average annual harvest volume during the past five years (2017–2021) amounted to 93,240,000 m^3 ha^{-1} $year^{-1}$ (Skogsstyrelsen, 2022a). The mean age at final felling throughout the past five-year average equals 100 years (Skogsstyrelsen, 2022b). Computation of biogenic carbon in living trees was done using biomass expansion factors. For above-stump tree biomass these were based on Marklund (1988) and for stump and root biomass on models by Petersson and Ståhl (2006). Within young stands, above-ground tree biomass was estimated by models by Claesson et al. (2001) and decay of coarse woody debris based on Kruys et al. (2002) and Sandström et al. (2007). SOC calculation on mineral soils relied on the Q-model (Ågren and Hyvönen, 2003) that computes continuous soil organic matter decomposition, and emission factors for peatland. Deadwood carbon was assessed with exponential decay rates from dead wood inflow following tree mortality (Harmon et al., 2000). During the simulations neither detrimental nor beneficial influences of climate change were included as the available tools in Heureka do only implement positive effects, i.e., increased biomass growth, but do not enable to anticipate negative effects, i.e., increased occurrence of calamities.

The reference levels for national harvest for sawlogs and pulpwood were based on GLOBIOM simulations under the absence of any representative concentration pathway (RCP) climate change model (Havlík et al., 2018; Lauri et al., 2021). These reference harvest levels worked as the absolute benchmark to which the additional roundwood harvest volumes of sawlogs from the scenarios were added. This increased harvest intensity amounted to the overall relative forest carbon difference and thus constituted the climate impact occurring within the forest system.

2.5. *Climate impact metrics*

The climate effect assessment via the global warming potential metric, GWP_{100}, was complemented with the absolute global temperature change potential (AGTP) as an additional climate metric along the cause-effect chain from emissions to climate change (Fuglestvedt et al., 2003, Myhre, 2013). In contrast to GWP_{100}, the AGTP accounts for timing of emissions and associated atmospheric dynamics. It is expressed in degrees of kelvin (K) and equals the response in global mean surface temperature at a certain point in time due to a shift in radiative forcing from a GHG pulse emission, i.e. CO_2, CH_4, or N_2O. Thus, AGTP considers timing of GHG emissions and their perturbation lifetimes which enables assessments of time dependent dynamics of (time dynamic) climate effects. Perturbation lifetimes of CH_4, and N_2O were 12.4 and 121 years, respectively, and the one from CO_2 was based on the Bern carbon cycle model (Joos et al., 2001, 2013), where the molecule remains airborne until it is taken up by oceans or the biosphere. The AGTP is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H-t)dt \tag{1}$$

where radiative forcing (RF), expressed in W m^{-2}, and the climate response function (R_T) constitute a convolution over the assessed time horizon (H) induced from a change in RF due to a pulse emission of a GHG *x*. The term AGTP is used in the following synonymously with the term temperature change.

3. Results & discussion

3.1. *Additional roundwood demand and impact on Swedish forests*

Fig. 3 shows the cumulative additional roundwood volume demand in form of sawlogs for both scenarios under bark. Overall, the full concrete frame phase-out until 2030 induces an increasing sawlog harvest until 2030 and beyond until 2070. Starting in 2021, the ATF scenario provokes a cumulative additional roundwood demand of 1.1 million (M)

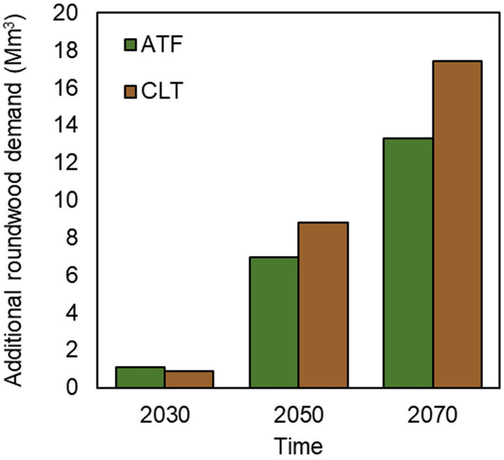

Fig. 3. Cumulative additional sawlog harvest volumes induced by the wood frame scenarios ATF and CLT respectively, given in million m^3 roundwood equivalents (under bark) as compared to the reference projection. ATF = average timber frame, CLT = cross-laminated timber. See Fig. 2 for more information on scenarios.

m^3 by 2030 and 13.3 Mm^3 by 2070. In contrast, the CLT scenario induces a slightly smaller cumulative harvest demand until 2030 with 0.9 Mm^3 due to the relative shift from timber-light frame dominance to cross-laminated timber. However, from 2030 until 2070 the CLT scenario requires about 1.4-times more compared to the ATF scenario which accumulates to 17.4 Mm^3. In terms of annual averages until 2050 this represents 0.1 Mm^3 $year^{-1}$ for the ATF scenario, and 0.3 Mm^3 $year^{-1}$ for the CLT scenario, which compared to the annual Swedish sawlog harvest volume during 2016–2020 would amount to only 0.7% and 1.6%, respectively (SFA, 2022). We thus find that the additional wood required for completely substituting concrete as a framing material in Swedish MFHC could easily be sourced entirely from national forests, even considering the more wood-intensive cross-laminated timber frame alternative.

In terms of the projected Swedish annual sawlog demand from 2020 until 2050 of 38.6 Mm^3 $year^{-1}$ (Lauri et al., 2021), the additional sawlog demand given in the scenarios would constitute a range from only 0.3%–0.4%. Carbon leakages within the wood-based sector would thus be virtually inexistent under the assumptions of the scenarios. This could guarantee real emission reduction within the Swedish forest sector, which without a self-sufficient national wood supply would require, e.g., a global carbon trading market to counteract carbon leakage (Pan et al., 2020). The additional average harvest area, including thinnings and final fellings, would extend from 0.7% (166,000 ha $year^{-1}$) under the ATF scenario to about 1.6% (383,000 ha $year^{-1}$) under the CLT scenario compared to present national productive forest land in Sweden, considering the entire time-frame from 2021 to 2070 and the current average sawlog harvest volume of 1.6 m^3 ha^{-1} (SFA, 2022). This is in accordance with the findings of Andersen et al. (2022), who, on a global level, note that only 3% of the forest area would be required by 2060 to meet future construction projections. The present study thereby can be seen as supporting the observation that global forest resources are more than sufficient for a future dominance of wood-based construction (Churkina et al., 2020), in addition to maintaining supply for other wood uses.

Increased wood harvest from Swedish forests could, however, compromise other ecosystem services, foremost biodiversity-related ones (Mazziotta et al., 2022; Chaudhary et al., 2016). These are typically found to be highest within old forest stands, i.e., 120–185 years old (Jonsson et al., 2020). Fig. 4 shows how the increased wood harvest following the scenarios provokes a decline in old forest areas in Sweden. This decline reduces the average old forest area of 1,150,000 ha $year^{-1}$ which is simulated from 2021 until 2070 under the reference projection. The ATF scenario causes an additional decline of −5300 ha $year^{-1}$ and the CLT scenario nearly the threefold with −14,500 ha $year^{-1}$. The additional decrease in old forest would thus range from −0.5% to −1.3% in comparison to the projected reference. In parts of the boreal forests of Sweden, where the limit for what is considered as old-growth forests is 140 years of age, this could, in addition to a decline in biodiversity-related ecosystem services, result in a non–optimal rotation age for carbon sequestration, which is estimated at 138 years (Peichl et al., 2022). In summary this supports the findings of Andersen et al. (2022) that wood-, in particular cross-laminated timber-based, construction may not hold a superior environmental performance in all environmental impact categories compared to concrete alternatives. Moreover, it highlights the apparently increasing ecosystem service trade-off that more bioeconomy-intensive forest management strategies may incur if aimed at maximizing wood harvest (Mazziotta et al., 2022).

3.2. *Climate impact of a complete wood-based multi-family housing construction*

3.2.1. *GHG balance including substitution effects and biogenic carbon*

The GHG balances of both scenarios including changes in fossil emissions, and biogenic carbon from HWPs as well as the forest system, are presented in Fig. 5 in a relative sense, i.e., as the difference to the reference projection. Both scenarios induce a negative net effect in the GHG balance, i.e., they provide a net climate benefit, when benchmarked to the concrete frame dominance in MFHC found in the reference projection. The dominating contributor in both scenarios is the substitution effect from the avoided fossil GHG emissions of the concrete

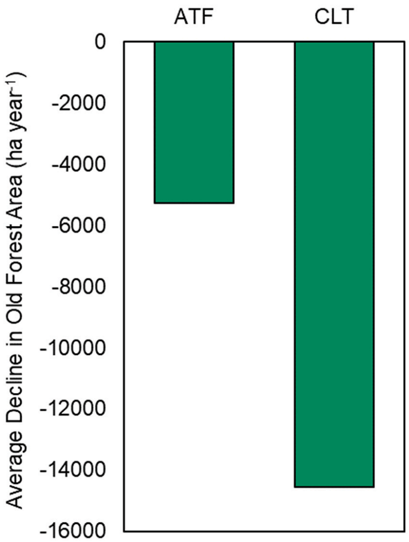

Fig. 4. Average annual decline in old forest area induced by the wood frame scenarios ATF and CLT respectively, given in ha $year^{-1}$, as compared to the reference projection. ATF = average timber frame, CLT = cross-laminated timber. See Fig. 2 for more information on scenarios.

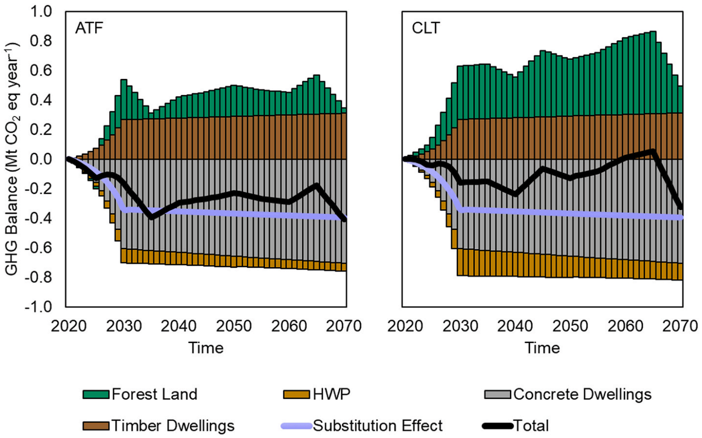

Fig. 5. Annual GHG fluxes of the ATF and CLT scenario as compared to the reference projection, i.e., the relative change in the GHG balance from a system perspective. Note that positive values correspond to emissions and that the substitution effect presented here corresponds only to the difference in fossil GHG balances. GHG = greenhouse gas, HWP = harvested wood product, ATF = average timber frame scenario, CLT = cross-laminated timber scenario. See Fig. 2 for details on scenarios.

dwellings for which the projected MFHC demand sets a cap for the achievable maximum (demand-perspective). By that, methodological shortcomings and a lack of data associated with a supply-perspective that necessitates assumptions of perfect substitutes (Hurmekoski et al., 2022) and shares of different end uses of wood products - e.g., the shares of different end uses of softwood sawnwood in Sweden - were circumvented. However, substitution effects which here are assumed constant may change over time. They may decrease under future decarbonization efforts of, e.g., the energy sector, or the concrete manufacturing industry, or due to increased recycling efforts in non-wood industries, as shown for Nordic wood-based construction in Myllyviita et al. (2022). In contrast they may however also increase due to, e.g., improved efficiencies in the wood manufacturing industry. As a consequence, biogenic carbon balances from the forest and the HWPs applied in construction may receive a larger or smaller relative importance in climate change mitigation. Biogenic carbon effects found here however are of minor magnitude in comparison to the substitution effect. The increased HWP carbon storage contributes moderately to the climate benefit whereas the forest system accounts for larger biogenic carbon losses due to increased harvests which fluctuate across the time-horizon due to regional forest age-class dynamics.

Overall, the ATF scenario leads to potential cumulative net GHG savings of around −1.0 Mt CO$_2$ eq by 2030, -6.8 Mt CO$_2$ eq by 2050, and -12.1 Mt CO$_2$ eq by 2070. This substantially outperforms the GHG savings from the CLT scenario, which cumulatively avoids a potential of −0.5 Mt CO$_2$ eq by 2030, -3.4 Mt CO$_2$ eq by 2050, and -4.7 Mt CO$_2$ eq by 2070. In comparison to the total GHG emissions in Sweden during the year 2021 of around 48 Mt CO$_2$ eq (SCB, 2023), the annual average emission mitigation from the ATF or CLT scenario would thus comprise 0.5% (−0.24 Mt CO$_2$ eq year^{-1}) or 0.2% (−0.09 Mt CO$_2$ eq year^{-1}), respectively.

This net climate benefit of both scenarios representing the wood-based replacement of concrete frame in Swedish MFHC thus corroborates earlier findings of a superior climate-performance of wood-based construction over concrete-based (Gustavsson et al. 2017, 2021; Piccardo and Gustavsson, 2021; Andersen et al., 2022; Churkina et al., 2020; Hildebrandt et al., 2017; Myllyviita et al., 2022). This outcome could be further substantiated if potential substitution effects of the "surplus" by-products being "cut-off" from the system boundaries were also considered. This is, however, simply not feasible since that would require information as to (i) the demand of all the end-uses that the "surplus" by-products could be used to manufacture, and (ii) their respective input mixes. If (i) and (ii) were at hand, then, still (iii) a considerable fraction of the "surplus" by-products would not lead to a substitution effect, since a considerable share would be used, e.g., for increased internal energy generation in sawmills, or for graphic or hygiene paper production. The exact amount used for these applications we are not able to estimate though.

Moreover, the results support earlier findings that increased biomass removal from forests induces a decrease of carbon accumulated in forest soils and trees (Seppälä et al., 2019; Soimakallio et al., 2021; Mazziotta et al., 2022) which can only partly be compensated for by the increase in the carbon pool of harvested wood products (Soimakallio et al., 2022). From a climate, as well as from a biodiversity perspective, this emphasizes the importance to aim for the most efficient wood utilization possible.

3.2.2. *Implications of different wood-based construction alternatives*

The increased climate benefit from timber light frame that dominates Swedish wood-based construction today (ATF scenario), compared to cross-laminated timber and glued-laminated timber, mainly originates from a lower wood use ratio per dwelling unit, which confirms the findings from Gustavsson et al. (2017) and Ruuska and Häkkinen (2012) (Myllyviita et al., 2022). However, this ratio can change substantially, for example given other material inventory data per building. More recent material inventories within a Swedish setting exist for both wood frame and concrete frame MFHC (Peñaloza et al., 2019; Piccardo and Gustavsson, 2021). However, for the purpose of this study, either an insufficient material breakdown for the concrete frame alternative was given (Peñaloza et al., 2019) or a specific market share breakdown into timber light frame, cross-laminated timber, and glued-laminated timber was infeasible (Piccardo and Gustavsson, 2021). Furthermore, different functional units among the studies impede a valid comparison between the wood frame and concrete frame dwellings.

In contrast to its less efficient wood use however do cross-laminated timber and glued-laminated timber allow for larger construction application ranges in comparison to timber light frame, e.g., due to improved dimensional stability and mechanical performance (Hurmekoski et al., 2015). This enables the applicability for high-rise building construction extending over conventional mid-rise MFH options. Especially in terms of sustainable planning of urban residential areas with more efficient use of space which aims for minimizing further land use change by land sealing, this may pose additional benefits over a conventional timber light frame application. This benefit is complemented by the potential that future cross-laminated timber may be produced using smaller wood assortments which would pose another advantage over timber light frame. Moreover, cross-laminated timber and glued-laminated timber--based construction enables better conditions for industrialized prefabrication, which can reduce related GHG emissions and on-site financial costs. In the light of "design for disassembly" principles, the option for industrialized prefabrication can thus offer waste reduction and further adds climate benefits at the end-of-life stage (Lehmann, 2013). Reduced waste and increased recyclability are however achievable for the wood-based construction types found in both the CLT and the ATF scenario. If considered properly during the building phase, wood-based construction thus allows in general for increased re-use potential of the renewable materials applied and by that improves the climate performance as well as other environmental indicators.

3.2.3. Role of future wood-based dwelling size on the atmospheric temperature change

Not only the choice of materials is of importance for enhancing environmentally sustainable housing construction. Another crucial aspect is the average dwelling size. The trend of larger dwellings contributes to higher environmental burdens (Ivanova and Büchs, 2022). Fig. 6 presents the change in atmospheric temperature induced by both scenarios when varying the current wood-based dwelling size by ± 20%. The temperature change is given in a relative sense, i.e., when benchmarked to the reference projection of concrete frame dominance in Swedish MFHC where the size of the dwelling remains stable, i.e., 57 m^2.

Decreasing the dwelling size from 57 m^2 to 45 m^2 increases the net climate cooling effect in both scenarios, while increasing the dwelling size to 68 m^2 reduces the net climate cooling effect. In fact, with a larger average dwelling size, the CLT scenario results in a slight net warming compared to the reference projection, i.e., the concrete frame dominated MFHC with 57 m^2. In contrast, an increased average dwelling size in the ATF scenario still produces a net climate cooling effect compared to the reference projection which is still slightly larger than the climate cooling effect of the CLT scenario under 57 m^2. A smaller average dwelling size is thus an additional important measure to reduce the climate impact, next to an increased wood-based construction.

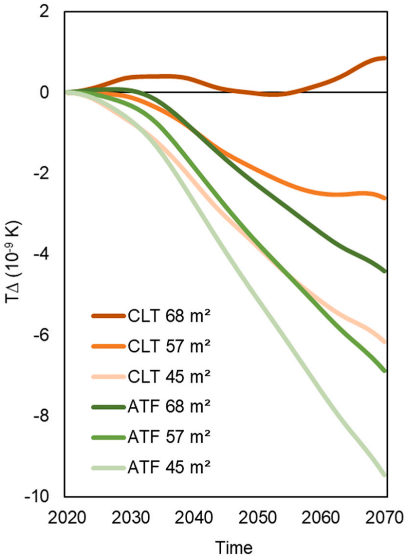

Fig. 6. Temperature change for the ATF and CLT scenario as compared to the reference projection, i.e., the relative change from a system perspective, and in dependence to a varying average dwelling size. ATF = average timber frame scenario, CLT = cross-laminated timber scenario. See Fig. 2 for details on scenarios.

It follows that a future MFHC applying the current wood-based construction types (ATF scenario) would be more climate beneficial than shifting to a cross-laminated timber-dominated MFHC, despite increasing the average dwelling size by 20%. In other words, a decreased dwelling size and extension of the timber light-frame dominated wood-based MFHC would maximize the climate cooling effect under the assumption of remaining on the middle-rise building level. As mentioned above this finding is mostly a result of the more efficient wood-use ratio in buildings based on timber light-frame in comparison to cross-laminated timber alternatives. A lower wood-use efficiency of the CLT scenario thus provokes a higher reduction in forest carbon due to increased harvest volumes required, as deducible from Fig. 5. In addition, the reduced wood-use efficiency is mirrored in the temperature change curves whose variation appears more pronounced for the dwelling size alterations under the CLT scenario compared to the ATF scenario.

A decreased dwelling size coupled with an increased wood use in MFHC would thus pose the most climate beneficial option, and also induce the least impact on local forests in terms of the risk of negative impacts on biodiversity. This combination of transforming the building stock into a more bio-based one together with the net saving of materials could thus add substantially to the so-called residents "handprint" potential due to the strong growth potential in residential carbon sequestration and storage capacities (Kinnunen et al., 2022). This would decrease the residents' usually heavy consumption-based lifestyle (Heräjärvi, 2019; Kinnunen et al., 2022) yet would require large and joint efforts from urban-planners, policy-makers, the scientific community, and the residents themselves (Kinnunen et al., 2022).

4. Conclusion

This study explores consequences of a complete replacement of concrete with different wood-based alternatives as frame material in Swedish multi-family housing construction (MFHC) from 2030. In addition to GHG fluxes and associated atmospheric temperature change, the study assesses implications as to the future state of Swedish forests induced by additional harvest volumes, notably in change of old forest area. Thereby we further the understanding of, firstly, the amount of wood that would be needed for completely substituting concrete in future MFHC in Sweden, based on an official housing demand forecast. Secondly, we estimate climate effects over time for different wood-based construction systems, as well as the role of dwelling size. Finally, we provide an assessment of climate-biodiversity trade-offs following increased wood use within a Northern European setting, using the indicator of change in the area of old forest.

The results show that the wood needed for the complete substitution of concrete as the — hitherto dominating — frame material in Swedish MFHC can be sourced entirely from national forests with only minor impacts on the forest carbon sink and the area of old forests. This holds true even considering the more wood-intense frame system solid cross-laminated timber. In addition, we find that a climate benefit of either -0.24 Mt CO_2 eq $year^{-1}$ for a timber light-frame or -0.09 Mt CO_2 eq $year^{-1}$ for a cross-laminated timber dominance is given, as compared to a continuation of the current concrete-dominated MFHC.

The timber light-frame system not only provides the largest climate benefit but also leads to the smallest reduction in the area of old forest.

In any case however, climate change mitigation from wood-based substitution comes with the trade-off of decreasing area of old forests. This is exacerbated using the cross-laminated timber system, due to a less efficient wood-use ratio per dwelling unit which also explains its inferior climate performance compared to the currently dominating wood-based construction type, timber light-frame. However, a ramp-up of the use of modern engineered wood product-based construction, notably cross-laminated timber, would expand the application range due to superior structural properties, thus further enabling substitution of concrete-based construction, e.g., in high-rise buildings.

Decreasing the average flat size in future wood-based MFHC by 20% yields additional climate change mitigation. The largest climate change mitigation is provided when smaller dwellings are built using the timber light-frame system. In contrast, MFHC with a 20% larger average dwelling size based on the cross-laminated timber system has a climate impact comparable with concrete-based construction with a current average dwelling size of 57 m^2.

Summing up, when aiming for increasing the share of wood-based construction, decreasing the average flat size would maximize not only the climate benefits, but would also minimize decline in old forest area, and reduce both urban and forest land use. To achieve this however, large, and joint efforts from urban-planners, policymakers, the scientific community, and the residents themselves are required.

CRediT authorship contribution statement

Maximilian Schulte: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ragnar Jonsson:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – review & editing. **Jeannette Eggers:** Conceptualization, Validation, Resources, Writing – review & editing. **Torun Hammar:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing. **Johan Stendahl:** Conceptualization, Validation, Resources, Writing – review & editing. **Per-Anders Hansson:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that the mutual funding by Swedish University of Agricultural Sciences and Stora Enso Oy may be considered as a potential competing interest.

Data availability

See Supplementary Material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138487.

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PAPER

Climate change mitigation from increased paper recycling in Sweden: conserving forests or utilizing substitution?

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Abstract

Climate change mitigation by increased paper recycling can alleviate the two-sided pressure on the Swedish forest sector: supplying growing demands for wood-based products and increasing the forest carbon sink. This study assesses two scenarios for making use of a reduced demand for primary pulp resulting from an increased paper recycling rate in Sweden, from the present 72% to 78%. A *Conservation* scenario uses the saved primary pulp to reduce pulplog harvests so as to increase the forest carbon sink concomitant with constant overall wood product supply. In contrast, a *Substitution* scenario uses the saved primary pulp to produce man-made cellulosic fibers (MMCF) from dissolving pulp replacing cotton fiber, implying increased overall wood product supply. Our results suggest that utilizing efficiency gains in paper recycling to reduce pulplog harvests is better from a climate change mitigation perspective than producing additional MMCF to substitute cotton fiber. This conclusion holds even when assuming the use of by-products from dissolving pulp making and an indirect increase in MMCF availability. Hence, unless joint improvements across the value chain materialize, the best climate change mitigation option from increased paper recycling in Sweden would seemingly be to reduce fellings rather than producing additional MMCF.

1. Introduction

The climate change mitigation potential of the forest-based sector is primarily based on the ability of forests to sequester carbon dioxide (CO_2) from the atmosphere and store it in its soils and biomass including storage in harvested wood products (HWPs) (EC 2021b). This potential can be complemented by (i) the substitution effect, i.e., potentially reduced greenhouse gas (GHG) emissions resulting from replacing more emission-intensive products and energy with wood-based alternatives (Hurmekoski *et al* 2021), and (ii) the feasibility and degree of recycling and use of recovered wood products (Lorang *et al* 2022).

Sweden is the second largest roundwood supplier in the European Union (EU) and has the largest forest area, 28 Mha (EUROSTAT 2024). At the EU level, two principally contrasting views on forest management exist to improve the forest sector's contribution to climate change mitigation. On the one hand, programs such as the EU Green New Deal aim to increasingly rely on bio-based resources - implicitly implying intensified forest management - in order to further substitution (EC 2021b). However, the highly intensive forest use in Sweden leaves little room for further increasing harvest rates (SCB and SLU 2023). On the other hand, other policy initiatives such as, notably, the EU's land use, land use change and forestry (LULUCF) regulation aim for strengthening the natural forest carbon sink (EC 2023). This poses a two-sided pressure on the Swedish forest sector in contributing to climate change mitigation.

One option for alleviating this conflict is increased circular wood use in the form of improved circularity and resource efficiency. This can either be achieved by aiming for long cascading use, e.g., timber frame becoming particleboard at the end-of-life, the latter being energy recovered when disposed (Thonemann and Schumann 2018), or through recycling of wood fiber for producing the same material again, e.g., wastepaper being recycled into recovered pulp which itself can replace primary (virgin) pulp in papermaking.

Paper and paperboard are the most recycled materials in Europe (CEPI 2022) and their utilization in form of recovered pulp is the most common wood product recycling process today (Lauri *et al* 2021). In the EU, the overall paper recycling rate was 71% in 2021 (EPRC 2022b) and in the same year it amounted to 72% in Sweden (FTI 2023). By 2030, the paper industries in the EU consider themselves ready to take circularity to a new level and endeavor to reach a 76% paper recycling rate (CEPI 2022), which is close to 78%, the maximum rate considered achievable, due to non-collectable and/or non-recyclable paper products such as hygiene papers (EPRC 2022a). Challenges to paper recovery are on the one hand reduced consumption of paper grades commonly recycled at high rates, e.g., graphic paper, and on the other hand increased demand for more complex paper products, such as technical papers, which require specialized recycling processes (EPRC 2022a). The remaining potential in increased paper recycling in the EU and Sweden in parallel with the pressures and expectations on the forest sector to reduce global warming, thus provokes the question how such an efficiency gain could best be used to mitigate climate change, reconciling the aforementioned contrasting policy objectives.

Within the EU, Brunet-Navarro *et al* (2017) state that increasing paper recycling would be a viable short-term climate change mitigation measure. On the product-level this was formerly found by Merrild *et al* (2009) highlighting the climate change mitigation effect from potential substitution credits as consequential to saved primary wood being used otherwise. Still on the EU level, Bais-Moleman *et al* (2018) confirmed a GHG reduction potential from jointly increasing recycling of paper and waste wood to a technical maximum rate relative to current practices. Lorang *et al* (2022) studied the climate effects of increased paper recycling on a national scale for France, by adding the recycling industry to an existing forest sector model. Climate effects from increased paper recycling were found to be highly dependent on whether primary and recycled pulp are considered perfect or imperfect substitutes. A slight climate benefit was given for perfect substitutability, i.e., a 1:1 replacement, and additional emissions given complementarity. For the Swedish forest sector however, the effect of additional paper recycling and use of recovered wood products remains rather undiscovered in climate impact assessments, while two contrasting options exist for potential climate change mitigation.

The first option implies using the recovered pulp over primary pulp to reduce pulplog (in the following synonymous with pulpwood) harvests in Swedish forests. The second option instead aims to use the saved primary pulp and thus the 'surplus pulplogs' (given unchanged harvest levels) to produce wood products with a high substitution effect potential such as textiles from man-made cellulosic fibers (MMCF) in form of viscose (Leskinen *et al* 2018). MMCF, today mainly produced from wood, account for about 6% of the global fiber market. Based on their technical properties MMCF sourced from wood can replace the more emission-intensive fibers made from cotton (Hurmekoski *et al* 2018) which currently dominate the global market together with polyester, holding shares of 22% and 54%, respectively (Leskinen *et al* 2018, Textile Exchange 2022, Hurmekoski *et al* 2023). Of the MMCF used for textile applications, viscose is most important with a dominant market share of around 80% (Textile Exchange 2022). The production of MMCF as well as global general fibers has for at least doubled since 1990 from 3 million tons (Mt) and 58 Mt to about 7.2 Mt and 113 Mt in 2021, respectively, and is foreseen to further expand due to projected increasing demand under a business as usual trend (Textile Exchange 2022). Substitution of the dominating, more emission intensive textile fibers polyester and cotton is thus seen as a major requirement for limiting global warming within the global textile industry, next to reducing overall growth in the sector (Textile Exchange 2022).

These two contrasting options for climate change mitigation mark the starting point for the present study, which aims to analyze the climate effects of an increased paper recycling rate in Sweden. Two scenarios based on the abovementioned options for how to utilize the additionally recovered pulp are defined, i.e., a *Conservation* scenario and a *Substitution* scenario. The overriding assumption in both scenarios is thereby a 1:1 replacement between primary pulp sourced from pulpwood and recovered pulp. The climate effects assessed are compared to a business-as-usual (BAU) reference, or baseline, scenario to account for the marginal change in the GHG balance. With the two climate change mitigation scenarios from increased paper recycling at hand, we set out to answer the research question '*Which is the best climate change mitigation scenario given an increased recycling of paper in Sweden - using recovered pulp to reduce fellings (of pulpwood) and thereby increasing the Swedish forest carbon sink, or producing MMCF to substitute for other textile fibers?*

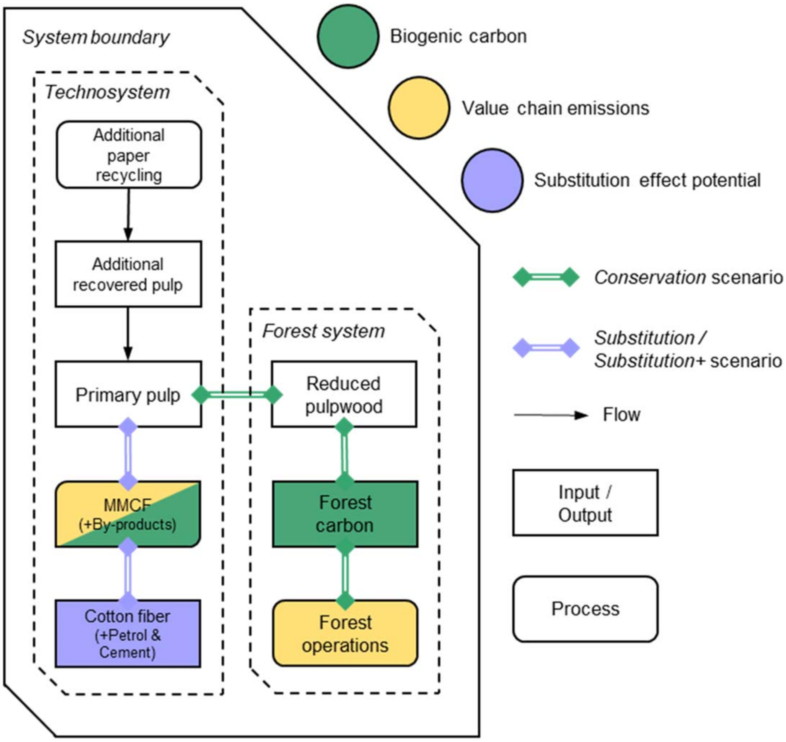

Figure 1. System boundary encompassing the marginal effects of additional paper recycling from the *Conservation and Substitution/ Substitution+* scenario on the biogenic carbon and fossil greenhouse gas balances from value chain emissions and potential substitution effects within techno- and forest system.

2. Methods

2.1. System boundaries & scenario set-up

Figure 1 shows the system boundaries of the study as given for the two scenarios making use of the additional recovered pulp arising from increased paper recycling, compared to the BAU reference situation. The BAU reference is characterized by maintaining the present 72% recycling rate of paper products in Sweden (FTI 2023) and a constant production of pulplog-based wood products. The system boundaries are divided into a technosystem and a forest system. The technosystem is set in Sweden considering the additional paper recycling until the additional primary pulp making, and in China, where the substitution of cotton fiber at the point of yarn making is assumed to occur. The forest system is solely set in Sweden. Within the systems, the changes in GHG balances due to increased paper recycling are accounted for in terms of biogenic carbon in forest biomass, and fossil emissions from the forest industry and substitution effects, i.e. potentially avoided emissions. The time horizon spans 80 years from 2020 until 2100, to account for the short- and medium-term climate effects. The modelling of both scenarios departed from the increased paper recycling leading to additional recovered pulp, which is assumed to fully replace and thus save primary pulp in papermaking.

The *Conservation* scenario assumes that the amount of saved primary pulp leads to a decrease in pulpwood harvests. Consequently, the scenario includes biogenic carbon changes in the forest within standing biomass, dead wood, and soil organic carbon, as well as changes in the fossil GHG balance induced by decreased forest operations and increased fossil emissions from enhanced paper recycling and pulp recovery. The *Conservation* scenario assumes an equal quantity of supplied wood products compared to the BAU reference situation.

In the *Substitution* scenario, the saved primary pulp is used to produce MMCF. Accordingly, there are additional fossil emissions from increased paper recycling, as well as from increased production of dissolving pulp and MMCF. The additional supply of MMCF is assumed to replace cotton fiber whose saved fossil

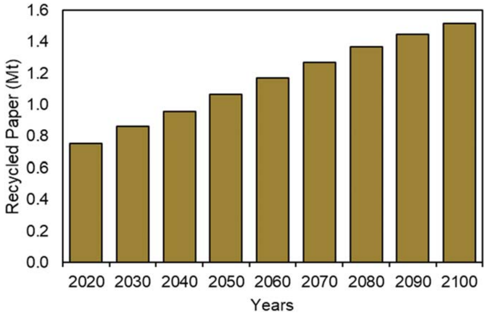

Figure 2. Projected recycled paper supply in Sweden from 2020 until 2100 under the business-as-usual (BAU) scenario, given in Mt.

emissions are considered as substitution effects. The substitution of cotton by MMCF is assumed to cancel out the additional biogenic carbon storage since this is similar among both fiber types. The fossil GHG balances are only accounted for from cradle-to-gate, since it is assumed that fossil emission differences between MMCF and cotton fiber appearing after the point of substitution, i.e., yarn making, from spinning, transportation to retailers, or end-of-life combustion, are similar (Lidfeldt *et al* 2022) and cancel out each other. The *Substitution* scenario assumes an increased supply of wood products as compared to the BAU reference or the *Conservation* scenario. By-products from the MMCF feedstock dissolving pulp production are considered to be used for internal energy recovery, i.e., no substitution effect arises from these. However, a sub-scenario of the *Substitution* scenario, in the following *Substitution+* scenario, considers possible avoidance of petrol and cement due to further processing and use of the by-products, and accounts for potential substitution effects and additional biogenic carbon storage accordingly. A description of this sub-scenario is given in section 2.2.

A key feature of the study is that only relative climate effects are assessed, i.e., the GHG differences between the BAU scenario and the *Conservation* and *Substitution* scenario, respectively. Changes in the greenhouse gas balances and potential climate change mitigation arise solely from the consequence of an increased recycled paper quantity. Climate effects are stated as 'additional' compared to the continuation of the BAU reference. A ceteris paribus assumption applied to the system boundaries is that the provision of other products than pulp and pulp-based products, e.g., by-products from the sawmilling industry, are not affected by the increase in the paper recycling rate. We disregard the GHG implications in the remaining wood manufacturing sector producing sawnwood, plywood, panels, or fuelwood. This is in line with Lorang *et al* (2022) who found that the effects on emissions in other wood manufacturing sectors are minor or negligible.

The functional unit of the *Substitution*/*Substitution+* scenario was the quantity of fiber produced given in Mt year^{-1}.

2.2. Modelling of the technosystem

At first, the BAU reference was defined. The modelling departed from the projection of recycled paper supply for Sweden from 2020 until 2100 as based on Global Biosphere Management Model (GLOBIOM) simulations under the absence of any representative concentration pathway (RCP) climate change model (Havlík *et al* 2018, Lauri *et al* 2021) as shown in Figure 2. The data on recycled paper supply were interpolated to annual values and converted into recovered pulp, using a conversion factor of 0.91 Mg Mg^{-1} (RISE 2022). Subsequently, the difference in recovered pulp among the BAU scenario (72% paper recycling), and either of the scenarios (78% paper recycling) constituted the 'saved' primary pulp quantity. The recovered pulp production ranged from placing the recovered paper into the pulper to the recovered pulp ready to be fed into the paper machine, where the point of substitution of the primary pulp by the recovered pulp was defined. Accordingly, the recovered pulp was not considered to be air dry but in a pumpable state. Substitute paper products from the recovered pulp, for which primary pulp was used before, were packaging grades (corrugated grades) for which no additional dispersing, deinking, or bleaching is required, which instead is often given for tissue papers or graphic papers that can also contain large shares of recovered pulp. The saved primary pulp quantity was subsequently converted into saved pulplogs (*Conservation* scenario) or MMCF replacing cotton fiber (*Substitution* scenario), based on the modelling steps displayed in Figure 3.

The *Conservation* scenario comprises converting the saved pulp quantity to pulplog equivalents and assessing the saved forest carbon. The pulplog quantity over bark, given in volume, is estimated by applying a conversion factor of 4.8 m^{3} pulplog, under bark Mg^{-1} pulp (FAO 2020) and an over bark to under bark coefficient of

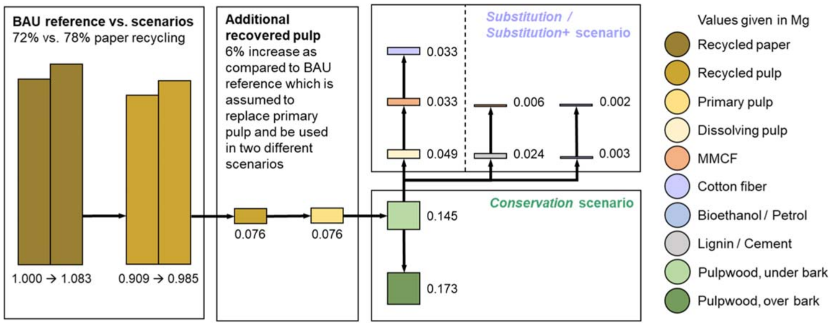

Figure 3. Conversion steps departing from the difference in recycled paper and recovered pulp between BAU reference and scenarios, ranging over additional saved primary pulp, the equivalent pulpwood quantity (Conservation scenario), the production of dissolving pulp and MMCF, substitution of cotton (Substitution scenario), as well as additional by-products and their substitutes petrol and cement (Substitution+ scenario), illustrated as based on 1 Mg of recycled paper under the BAU reference.

0.90 m^3 (FAO 2020). The result - the saved pulplog quantity given in m^3 over bark - was used to calculate the biogenic carbon implications in the forest system using the forest decision support system Heureka PlanWise (section 2.3).

Modelling the *Substitution*/*Substitution*+ scenario also entails converting the saved pulp quantity into equivalent pulplog volumes by applying conversion factors of 4.8 m^3 pulplog Mg^{-1} pulp and 0.90 m^3 under bark m^{-3} over bark, as for the *Conservation* scenario. The volume of pulplogs, over bark was converted into mass applying a density of 0.40 Mg m^{-3} (FAO 2020). The mass in pulplog equivalents was used to calculate the quantity of dissolving pulp, which could be produced from the saved pulp amount using a coefficient of 3.0 Mg pulplog Mg^{-1} dissolving pulp (Lidfeldt *et al* 2022). In Sweden, two major production sites exist producing dissolving pulp which is dedicated for MMCF. Domsjö mill (Domsjö Fabriker 2022) located in Västerbotten, northern Sweden, using both hard- and softwood, and Södra mill (Södra 2023) located in Blekinge, southern Sweden, which uses mainly birch hardwood. In this study, we based the modelling of dissolving pulp production on Lidfeldt *et al* (2022) and assumed the production to rely on softwood, as it is practice at Domsjö Fabriker (2022). Producing dissolving pulp from pulplogs results in the by-products hemicellulose and lignin, from the digestion process and bark. The *Substitution* scenario assumes to rest the fate of the by-products on internal energy recovery which is the general use in Sweden, and which does not lead to a substitution effect potential (Skytt *et al* 2021). The *Substitution*+ scenario, in contrast, assumes that the by-products are further processed, based on the practice at Domsjö Fabriker. Here, both by-products are derived after drying the washed wood feedstock. The by-product hemicellulose is mainly fermented in an ethanol plant to produce bioethanol serving as a biofuel to be blended with petrol in cars. Lignin, which is produced along the process of bioethanol making, is used as an admixture in concrete to improve its flow properties and strength characteristics thus reducing the need for cement in concrete structures. The yield ratio of the by-products per unit of dissolving pulp produced in 2022 was 7% bioethanol, and 49% dried lignin (Domsjö Fabriker 2022). Accordingly, the *Substitution*+ scenario accounts for bioethanol and concrete admixture, in terms of the additional biogenic carbon storage, as well as additional value chain emissions, and potential for substitution effects. A replacement ratio of 1:0.62 was assumed for bioethanol considering its lower heating value of 26.7 MJ kg^{-1} and that of petrol, 43.4 MJ kg^{-1}. For the lignin-based concrete admixture, a ratio of 1:0.25 with cement was assumed, based on a 25 weight percentage (wt%) of cement (Sutradhar *et al* 2023), while for the biogenic carbon storage in the lignin-based admixture a half-life time of 35 years, i.e., consideration of a 'long-lived' wood product, was assumed (Rüter *et al* 2019). After dissolving pulp is produced, it was modelled to be transported to central Asia, where the production of the MMCF viscose is assumed to occur. The transport was simulated by a bulk carrier marine vessel departing in Sweden with the destination of China, whose fossil emissions were based on NTMCalc 4.0 (NTM 2024). Viscose production was modelled based on Lidfeldt *et al* (2022). Table 1 summarizes the quantities of the required resources such as chemicals and energy for the production process with a yield ratio of 1.5 Mg dissolving pulp Mg^{-1} viscose. The mass of viscose given in fiber was assumed to replace for conventional cotton fiber, since technical properties and production processes of cotton are more similar to wood-based fibers, compared to polyester fiber (Hurmekoski *et al* 2018). Cotton fiber production was assumed as a global market average. The replacement ratio between viscose and cotton fiber was assumed to be 1:1, based on the mass ratios of the different textile fibers (1 kg viscose fiber replacing 1 kg cotton fiber).

Table 1. Inputs for MMCF production (Substitution/ Substitution+ scenario) given for 1 kg of viscose fiber, based on Lidfeldt *et al* (2022).

Inputs	Quantity	Unit
Dissolving pulp	1.5	kg
Carbon disulfide	0.062	kg
Chemical inorganic	0.011	kg
Electricity	2.535	MJ
Heat	3.447	MJ
Heat, other than natural gas	9.282	MJ
Sodium chloride	0.085	kg
Sodium hydroxide	0.501	kg
Nitrogen, liquid	0.032	kg
Oxygen, liquid	0.013	kg
Sodium hypochlorite	0.107	kg
Sulfur dioxide	0.141	kg
Sulfuric acid	0.048	kg
Zinc monosulfate	0.010	kg
Outputs	Quantity	Unit
Viscose fiber	1	kg

One sensitivity analysis was conducted on the *Conservation* and the *Substitution*+ scenario to test the influence of the primary pulp to pulplog ratio (pp-ratio) by increasing or decreasing it by 20%, while primary pulp was assumed to be a perfect substitute for recovered pulp. The pp-ratio is thus the amount of pulplogs necessary to produce one ton of pulp. This affected the climate effects as consequential to, either changed pulplog saving potentials (*Conservation* scenario), or altered substitution effect potentials (*Substitution*+ scenario). In addition a second sensitivity analysiswas performed on the *Substitution*+ scenario altering the replacement ratio between MMCF and cotton fiber by ±20% to take account of a differing degree of substitution or complementation, respectively.

Life cycle inventory data for the dissolving pulp, and MMCF, i.e., viscose production, were based on Lidfeldt *et al* (2022) and the data for cotton fiber as well as all other underlying emission data were taken from the ecoinvent 3.9 database (Wernet *et al* 2016). See the Supplementary Material for details.

2.3. Modelling of the forest system

Biogenic carbon balances in Swedish forests were simulated for the BAU scenario and the *Conservation* scenario using the forest decision support system Heureka PlanWise version 2.22.0.0 (Lämås *et al* 2023), similar as done in Schulte *et al* (2023). For the *Substitution* scenario, this was not required since the biogenic carbon balance was the same as under the BAU scenario. The forest system was based on National Forest Inventory (NFI) data from 2020, limited to the productive forest land in Sweden where tree growth per ha and year is larger than 1 m^3, an area of around 24,000,000 ha. On the productive forest land, voluntarily and formally set-aside areas were excluded from the assessment. The mean wood volume on productive forest land equals 139 $m^3\ ha^{-1}$ (excluding the nature reserves and set-aside lands) and the mean age at final felling throughout the past five-year average equals 100 years (SFA 2024a). The average annual harvest volume during the past five years (2017–2021) amounted to 93,240,000 m^3 over bark (SFA 2024b).

Computation of biogenic carbon in living trees was done using biomass expansion factors. For above-stump tree biomass these were based on Marklund (1988) and for stump and root biomass on models by Petersson and Ståhl (2006) while decay of coarse woody debris was based on Kruys *et al* (2002) and Sandström *et al* (2007). Soil organic carbon (SOC) calculation on mineral soils relied on the Q-model (Ågren and Hyvönen 2003), which computes continuous soil organic matter decomposition, and emission factors for peatland. Deadwood carbon was assessed with exponential decay rates from dead wood inflow following tree mortality (Harmon *et al* 2000). During the Heureka simulations, neither favourable nor detrimental effects of climate change on the forest were considered since the available tools in the software do not implement negative effects, i.e., increased occurrence of calamities. This does not permit a balanced assessment along with the availability of accounting for positive, i.e., growth enhancing, influences.

The reference forest carbon levels originated from the official Swedish forest impact analysis (Skogliga konsekvensanalys), in the following ‘SKA’, conducted by the Swedish Forest Agency on behalf of the government of Sweden and in collaboration with the Swedish University of Agricultural Sciences (SLU) (Eriksson *et al* 2022). Here the scenario ‘dagens skogsbruk’, i.e., ‘business as usual’ was chosen as it assumes to continue current forestry practices during the simulated time horizon. This concerns both land use (areas of nature conservation provisions, consideration areas and timber production land), as well as the management methods that are applied today, for example in terms of regeneration methods, choice of tree species and extent of fertilization and clearing. This scenario uses the same felling intensity (felling in relation to growth on timber production land) as during the 2011–2015 period, which corresponds to 79% of net growth (gross growth - natural decline) on timber production land.

Reference levels for national harvest projections of sawlogs and pulpwood were based on simulations of GLOBIOM under the absence of any RCP climate change model (Havlík *et al* 2018, Lauri *et al* 2021).

For the *Conservation* scenario, the reference harvest levels worked as the absolute benchmark against which the saved pulpwood harvest volumes were compared to. The saved pulpwood harvest was modelled by, e.g., reduced thinning intensities, or changed rotation lengths. The decreased harvest intensity, given in m^3, amounted to the relative forest carbon difference, given in Mg C, and constituted the climate impact occurring within the forest system given in biogenic CO_2.

2.4. Climate impact metrics

The assessment of the climate impact was done using the metric of global warming potential (GWP_{100}) and was complemented with the absolute global temperature change potential (AGTP) (Forster *et al* 2021). The AGTP accounts for timing of emissions, their perturbation lifetimes and associated atmospheric dynamics, which the GWP_{100} omits. It is expressed in degrees of kelvin (K) and equals the response in global mean surface temperature at a certain point in time due to a shift in radiative forcing from a GHG pulse emission, i.e., from CO_2, CH_4, or N_2O. Thus, AGTP enables assessments of time dependent dynamics of climate effects. Perturbation lifetimes of CH_4, and N_2O were 12.4 and 121 years, respectively, and that of CO_2 was based on the Bern carbon cycle model (Joos *et al* 2001), which simulates the molecule to remain airborne until it is taken up by either oceans or the biosphere. The AGTP is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H - t) dt \tag{1}$$

where radiative forcing (RF), expressed in $W\,m^{-2}$, and the climate response function (R_T) form a convolution over the assessed time horizon (H) induced from a change in RF due to a pulse emission of a GHG *x*. The term AGTP is used in the following synonymously with the term temperature change.

3. Results & discussion

3.1. Additional recovered pulp, savings in pulplog harvest, and increased MMCF supply

Figure 4 shows the additional recovered pulp amount as induced by the simulated increased Swedish paper recycling, to the rate of 78% as compared to the current 72%. The resulting annual average addition of recovered pulp amounts to about 0.09 Mt, which equals 0.8% of the annual pulp production in Sweden under 2022, 11.8 Mt (Swedish Forest Industries 2023). In terms of the *Conservation* scenario, this represents on average 0.42 Mm^3 pulplog equivalents per year to be saved from harvest over the entire time horizon of this study. Over the past five years, the average annual pulplog harvest volume in Sweden amounted to about 31.6 Mm^3 (SFA 2024b). The pulplog harvest savings found here accordingly represent about 1.3%, a decent saving potential when considering that the current supply of pulp-based products would remain constant.

Under the *Substitution/Substitution+* scenario, the 0.09 Mt annual average addition of recovered pulp led to an increase in dissolving pulp production of 0.03 Mt (using 'freed up' pulplogs). This equals a production increase of about 8% when considering the sum of dissolving pulp volumes produced at Domsjö Fabriker (2022) of 178,000 Mg and Södra of 155,000 Mg (Södra 2023) during 2022. In terms of additional MMCF, the increase amounts to around 0.02 Mt as an annual average. This represents only a very small addition—0.3% - compared to the global annual production of viscose, which was 5.8 Mt in 2021 (Textile Exchange 2022).

3.2. Climate change mitigation from increased paper recycling in Swe

3.2.1. Aiming for conserving forests or for utilizing substitution?

The cumulative GHG balance of the *Conservation* and *Substitution/Substitution+* scenario from 2020 to 2100 is displayed in Figure 5 where negative values indicate a benefit to the climate. Overall, either scenario induces a climate change mitigation effect, as compared to the continuation of the BAU reference, i.e., maintaining the current 72% paper recycling rate. This highlights previous findings that additional paper recycling, may be seen as a viable mean to reduce net GHG emissions within the forest-based sector, given an effective substitution of primary pulp by recovered pulp (Merrild *et al* 2009, Brunet-Navarro *et al* 2017, Lorang *et al* 2022). However, the *Conservation* scenario has a distinctly larger GHG mitigation potential than the *Substitution/Substitution+* scenario. The most effective climate change mitigation from increased paper recycling in Sweden found here is

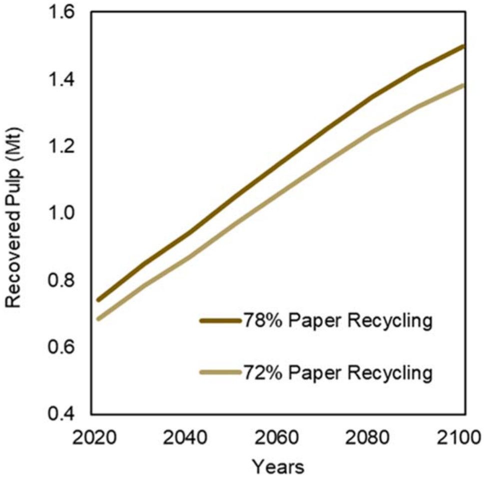

Figure 4. Recovered pulp quantity under the current paper recycling rate of 72% and under the target rate of 78% paper recycling. The saved pulp quantity equals the difference of the two lines and constitutes the starting point of the *Conservation and Substitution / Substitution +* scenario, respectively.

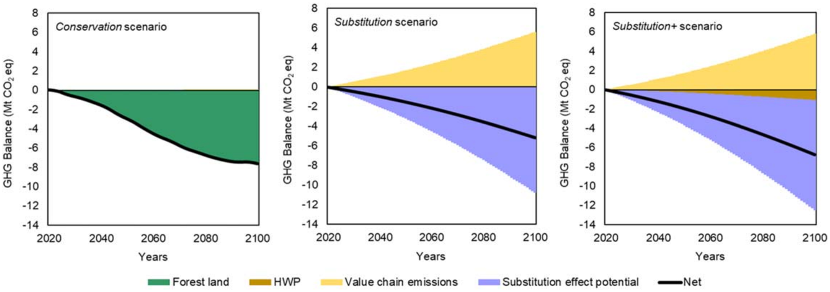

Figure 5. Cumulative GHG balances of the Conservation and Substitution/Substitution+ scenario making use of the "saved" primary pulp amount from the additional recovered pulp. Note: Negative values indicate reduced GHG emissions.

thus given when aiming for conserving forests in form of saving the additional efficiency gain by omitting pulplog harvest.

The *Conservation* scenario has an additional cumulative mitigation of −0.7 Mt CO_2 eq within the first 10 years from 2020–2030. The additional biogenic forest carbon almost exclusively contributes to this outcome with 99% as a consequence of the decreased pulplog harvest whilst fossil emissions from the additional paper recycling activity or saved forest operations are negligible with the remaining 1% contribution. In the long term, i.e., from 2020–2100, this cumulative mitigation is increased to −7.6 Mt CO_2 eq. The *Conservation* scenario could thus contribute to Sweden's required additional biogenic carbon sink under the EU LULUCF regulation. Here the requirements for Sweden are the highest among all EU member states and call for an increase of −4.7 Mt CO_2 until 2030 (EC 2021c, 2021a). The *Conservation* scenario could thus add to about 15% to reach the EU LULUCF 2030 target for Sweden.

However, this outcome of the *Conservation* scenario is connected to uncertainty factors. The first is the omission of detrimental climate change related effects such as forest disturbances, likewise beneficial effects, such as CO_2 fertilization. As mentioned previously, these were omitted due to insufficient ability of the forest modelling tool Heureka PlanWise to simulate these effects appropriately (Mazziotta *et al* 2022). This poses a great need for improving forest-based system's analysis, not only for the purpose of assessing climate effects. The second uncertainty factor is the location where the pulplog harvest savings would occur across Sweden. Within the same time frame would saving pulplog harvest, e.g. via reduced thinnings, in southern Sweden induce a larger carbon sink effect, than in northern Sweden, foremost due to the latitudinal climate and forest growth gradient (Skytt *et al* 2021). However, since negative impacts on forests from climate change such as forest fires and bark beetle risks have a similar spatial occurrence, these could offset this gain. A third uncertainty factor, here outside the system boundaries, is international forest carbon leakage. Commonly, leakage can largely outweigh additional forest carbon sinks in the region or country where decreased harvests occur (Lundmark 2022). However, in this study international forest carbon leakage can be neglected since the provision of Swedish wood products was not reduced, and thus no other harvest had to compensate elsewhere. Finally, a lower demand for pulpwood may not in any case lead to a decreased harvest rate. Pulpwood harvest quantities, as well as recovered paper quantities, are influenced by market dynamics, so that pulpwood may still be harvested but used, e.g., for energy generation. Inclusion of these market dynamics was however not part of this study.

The *Substitution* scenario yields a short-term cumulative climate change mitigation of -0.5 Mt CO_2 eq between 2020–2030. In the long-term, this increased to -5.0 Mt CO_2 eq between 2020–2100. This outcome arises from the potential substitution effect of replacing cotton fiber contributing to 66% of the total climate impact, which is larger than the fossil value chain emissions of additional paper recycling, dissolving pulp making, international transport, and viscose fiber production taken together, which add to the remaining 34% contribution. The *Substitution+* scenario excels over the *Substitution* scenario with yet additional 18% climate change mitigation during 2020–2030 (-0.6 Mt CO_2 eq), and 23% during 2020–2100 (-6.7 Mt CO_2 eq). Here the additional substitution effect potential including that from by-products contributes cumulatively to 63% of the GHG balance, and added biogenic carbon storage from the lignin-based concrete admixture to 6%, while the remaining 32% contribution arise from the fossil value chain emissions. Comparing these results to other national assessments analyzing additional climate change mitigation from increased paper recycling is difficult, first due to a lack of equivalent studies, and varying definitions of reference situations or system boundaries of somewhat comparable studies (Bais-Moleman *et al* 2018, Lorang *et al* 2022). However, one benchmark to the short-term cumulative mitigation of -0.5 Mt CO_2 eq found for the *Substitution* scenario between 2020–2030 can be the national fossil GHG emissions of Sweden during the equivalent past time frame 2010–2020 amounting to 54.2 Mt CO_2 eq (SCB 2024).

The three central assumptions that influence the outcome of the *Substitution*/*Substitution+* scenario are firstly the conversion ratio from recovered pulp, over pulplogs to the MMCF viscose, secondly the degree of the potential substitution effect, and thirdly, which products are replaced. In this study a mass ratio of one ton viscose per 5.3 tons pulpwood was given, while elsewhere more efficient ratios of approximately 2.5 tons of oven-dry wood are stated to be required for producing one ton of cellulosic fiber (Hassegawa *et al* 2022). This difference can underline the large variability which is present across production facilities along MMCF value chains considering their climate impact (Lidtfeldt *et al* 2022). As to the degree of the potential substitution effects, a perfect substitution, i.e., a replacement ratio of 1:1, was assumed between (i) recovered pulp and primary pulp, and (ii) viscose fiber and cotton fiber, respectively. Lorang *et al* (2022) highlight that whether increasing recovered pulp production yields climate change mitigation depends on whether perfect substitution or complementarity — i.e., only partial substitution and partial complementation of GHG emissions — is assumed. Indeed, complementarity in the form of overproduction is common in the apparel sector. Globally it is assumed that 10%–40% of all garments produced yearly, i.e., 15,000–45,000 Mt, are never sold or worn, but landfilled, or destroyed elsewise (WGSN 2023). This underlines that overproduction is not only commercially ineffective, but greatly compromises the garments industry's sustainability, or climate agenda. Future research should therefore add to the current understanding of complementarity or substitutability between wood-based and non-wood based products, e.g. via econometric analysis (Hurmekoski 2024). Meanwhile, assuming alternative products from pulpwood than MMCF, such as wood panels, or bioenergy would have led to different outcomes of the *Substitution*/*Substitution+* scenario. However, this could have implied a lower climate change mitigation since out of a large bandwidth the wood use for textile application was shown to yield the highest substitution effect on the product level (Leskinen *et al* 2018).

Fossil GHG emissions along forest value chains in Sweden must reduce substantially to align with Sweden's target of reaching carbon neutrality by 2045 (Government Offices of Sweden, Ministry for the Environment 2020). Global decarbonization requirements also apply to the substitution effects, i.e., the potentially avoided fossil GHG emissions from global production of cotton fiber, petrol, or cement. Fossil GHG reductions or even fossil GHG phase-outs may however differ greatly depending on the geography of sourcing and production. Decarbonization requirements thus imply important dynamics in the fossil GHG balances of the *Substitution*/*Substitution+* scenario which were however not considered here due to their unknown development. Accordingly, caution is warranted as to the uncertainty connected to the fossil GHG balances presented in this study. In the desired state of fully achieving decarbonization across the industrial sectors involved in wood

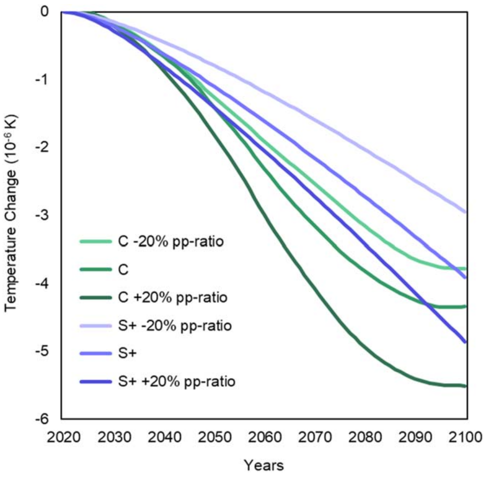

Figure 6. Atmospheric temperature change of the *Conservation and Substitution*+ scenario including the sensitivity analysis in which the primary pulp to pulplog ratio (pp-ratio) is increased or decreased by 20%, respectively. This implies changed pulplog savings in the *Conservation* scenario and altered dissolving pulp and thus MMCF and by-product availability in the *Substitution*+ scenario. Note: C = *Conservation scenario*, S+ = *Substitution*+ scenario.

product systems (including those of the substituted products), the role of fossil GHG balances would fade and that of biogenic carbon increase.

3.2.2. The role of pulplog saving efficiency, by-products, and replacement ratio between MMCF and cotton fiber

Figure 6 displays the sensitivity of the results from the *Conservation* and *Substitution*+ scenario depending on the pp-ratio, i.e., primary pulp to pulplog ratio. The pp-ratio alters the saved pulplog efficiency in the *Conservation* scenario, as well as , in the *Substitution*+ scenario with consequential changes in the dissolving pulp, and thus MMCF availability.

Overall, changing the pp-ratio has moderate effects on the climate change mitigation of either scenario. A change of ±20% in the pp-ratio increases the climate cooling of the *Conservation* scenario by +28% or decreases it by −15%, while for the *Substitution*+ scenario this effect amounts to +26% or −26%. However, irrespective of an improved primary pulp to pulplog ratio, and inclusion of the by-products' additional substitution effect and biogenic carbon storage, the overall inferior climate change mitigation compared to the *Conservation* scenario remains. Only if a decreased pulplog saving efficiency under the *Conservation* scenario and simultaneously an improved dissolving pulp and thus MMCF availability, as well as application of the by-products under the *Substitution*+ scenario is given, would the *Conservation* scenario induce an inferior climate cooling. This outcome highlights that it requires joint improvements across the industry to generate a superior climate change mitigation from MMCF production than can be achieved by means of reduced pulplog harvest activity. Indeed, next to the use of by-products, several developments including industrial initiatives and pilot tests are globally underway investigating more sustainable and innovative production technologies of MMCF (Textile Exchange 2022). One approach is the use of recovered post-consumer textile fiber as a raw material for viscose production. This method has shown promising potential to reduce not only climate impacts (Paunonen *et al* 2019), but also the area of land use per unit of fiber (Hammar *et al* 2023). However, still in 2021 only a very small share of less than 1% of the global fiber market was based on recycled textiles (Textile Exchange 2022) so that fundamental developments are required towards a more sustainable textile industry based on recovered fiber.

In this study, the conservation of forests was found to lead to the largest climate change mitigation. This finding is further substantiated in the second sensitivity analysis (Figure 7) when a 1:0.8 replacement ratio between MMCF and cotton fiber is assumed in the *Substitution*+ scenario. This highlights the implications as to the climate effects when only imperfect substitution between MMCF and cotton fiber is assumed which was found by recent econometric analysis (Hurmekoski 2024). In contrast, reaching comparable climate change mitigation as the *Conservation* scenario by MMCF substituting cotton fiber requires an ambitious replacement

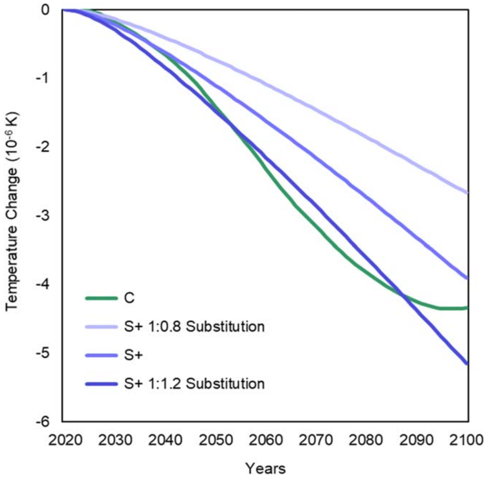

Figure 7. Atmospheric temperature change of the *Conservation and Substitution*+ scenario including the sensitivity analysis in which the replacement ratio of MMCF for cotton fiber is changed by ±20%, respectively. This implies either partial complementarity among the two fiber types (1:0.8 replacement ratio), or improved substitution conditions (1:1.2 replacement ratio). Note: C = *Conservation scenario*, S+ = *Substitution*+ scenario.

ratio of 1:1.2, which could highlight aforementioned need for concerted substantial production efficiency increases, property improvements, or demand changes for MMCF.

Regardless of the type of additional fiber produced for textile making, a more moderate consumption within a sufficiency-driven business model could thus further enhance the contribution to a more sustainable textile industry (Garcia-Ortega *et al* 2023) and combat the abovementioned overproduction in the apparel sector. The assumed additional MMCF fiber being generated in the *Substitution*/*Substitution*+ scenario is based on an improved circular economy principle, i.e., through increased paper recycling, within a growth-oriented economy, thus aligning well with and endorsing business-as-usual production practices. However, efficiency gains as presented in this study risk facilitating rebound effects which may compromise the environmental gains achieved (Bocken and Short 2016) and thus seriously limit sustainability. A sufficiency-driven business model - instead of a growth-oriented—rather seeks to curb general resource consumption by reducing demand via education and consumer engagement and focuses on satisfying 'needs' instead of promoting 'wants' (Bocken and Short 2016) thereby offering potential to avoid ineffective overproduction. Extended lifetimes of already existing textiles through, e.g., improved fiber quality and garment making, or reuse of the textile for another purpose can be measures to not only reduce carbon emissions, but at the same time also water consumption and waste generation.

Indeed, next to the climate effects studied here water consumption is a crucial environmental impact category typically included in assessments studying textile systems. The *Substitution*/*Substitution*+ scenario could, although inferior as to climate change mitigation compared to the *Conservation* scenario, therefore, bear an additional water saving potential given that the saved water consumption of cotton production outweighs the one of dissolving pulp production and viscose making (Shen *et al* 2010). Quantification thereof was, however, no aim of this study. On the contrary does the *Conservation* scenario bear additional environmental benefits such as those related to an enhanced biodiversity in Swedish forests due to decreased pulpwood harvest (Mazziotta *et al* 2022) for which indicators such as the area of old forest (gammal skog), tree species mixtures, or dead wood quantity per forest area could be considered (Jonsson *et al* 2019). Detrimental consequences from indirect land use change, on the contrary, could be abated following the *Substitution*/*Substitution*+ scenario, as cotton cultivation can displace cultivation of other crops to other geographies. Given the assumption of a real substitution of cotton fiber by MMCF, and an average cotton yield of around 3.2 t ha^{-1} $year^{-1}$ (FAO 2023), the additional viscose supply could imply saving agricultural land of about 64,000 ha dedicated for cotton cultivation, which could be used elsewise. Consequently, a distinct trade-off between environmental impacts exists for the two general options studied here for how additional paper recycling in Sweden can mitigate climate change, which must be considered when evaluating the sustainability of each of them.

4. Conclusions

There is considerable two-sided political pressure on the Swedish forests to increase the biogenic carbon sink through enhanced forest carbon sequestration while at the same time cater for a continuously growing demand for wood-based products. This suggests that increased circularity could be a way to alleviate this pressure. With that background, this study explores how increased paper recycling in Sweden could best be used to mitigate climate change. More specifically, we analyse whether conserving forests or exploiting substitution effect potentials results in superior climate change mitigation from an increase in paper recycling, given that the resulting additional supply in recovered pulp replaces primary pulp. Two overall scenarios are put forward. The first - *Conservation* scenario - keeps the supply of pulp products constant and uses the exempt primary pulp quantity to reduce pulplog harvests in Swedish forests. The second - *Substitution* scenario - makes use of the freed up pulplogs (with unchanged fellings) to produce MMCF from dissolving pulp in order to exploit potential substitution effects by replacing cotton fiber. A sub-scenario, *Substitution+*, furthermore accounts for the role of by-products from dissolving pulp making.

The results suggest that the largest climate change mitigation effect can be achieved if an increase in Swedish paper recycling is used to reduce pulplog harvests and enhance the forest carbon sink, rather than producing additional pulp-based MMCF with unchanged pulplog harvests. Increasing the paper recycling rate in Sweden could thus be used to decrease the harvest pressure on national forests and simultaneously contribute to the country's LULUCF-target for 2030. This conclusion is reinforced when assuming imperfect substitution among MMCF and cotton fiber, but also considering the substitution effect potential from by-products of the dissolving pulp making, together with an improved dissolving pulp availability. At last, climate change mitigation from reduced Swedish pulplog harvests thanks to increased paper recycling in Sweden would furthermore align well with a more efficient and sufficiency-based textile business relying on constant textile supply levels.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that the mutual funding by Swedish University of Agricultural Sciences and Stora Enso Oy may be considered as a potential competing interest.

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The forest-based sector can mitigate climate change by storing carbon in forests and in wood products and by replacing more emission-intensive products, i.e., substitution effects. However, trade-offs prevail, and quantification is complex. This thesis aims at improving climate impact assessments of forest-based systems. The findings provide valuable insights about methodological decisions and the resulting impact on the climate change mitigation potential of forests, wood products and substitution effects.

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