The role of biobased building materials in the climate impacts of construction

Effects of increased use of biobased materials in the Swedish building sector

Doctoral Thesis

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“Here, it’s a constantly changing topographical map flowing and shifting around the pole in ripples 10,000 years wide.
So tell me, how will all this be greatly improved by an oil pipeline?
By a shopping mall?”

Dr. Jonathan Osterman
a.k.a. Dr. Manhattan

ABSTRACT

Climate change must be mitigated to avoid irreversible impacts. A significant share of the climate impacts can be attributed to the construction sector and specifically to cement production. Thus, one of several mitigation strategies is to identify commonly used materials with high climate impacts (during their extraction, service life and disposal) and replace them with biobased materials in construction. Life cycle assessment (LCA) has been used to demonstrate the climate benefits of such a shift, but forest complexities create uncertainty as LCA practitioners traditionally omit certain key aspects.

This thesis is based upon studies designed to enhance understanding of the effects of increasing use of biobased materials in climate change mitigation of construction works with a life cycle perspective. Research questions were formulated focusing on identifying non-traditional LCA methodology aspects and assessing the climate impact effects of increasing the use of biobased materials while accounting for these aspects. The methods applied include dynamic LCA combined with forest carbon flux data and the analysis of multiple scenarios with different approaches. Case studies on diverse construction works (a building, a small road bridge and the Swedish building stock) and their benchmarks were used.

Most scenarios analysed result in impact reductions, confirming that increasing use of biobased materials decreases the climate impact of construction. The inclusion of non-traditional aspects affected the results, but not this general outcome. Results show that the climate mitigation potential is maximized by simultaneously implementing other strategies, such as increased use of low-impact concrete and renewable energy. Results also illustrate that assuming biobased building materials are climate neutral is an oversimplification, because their climate impact depends on case-sensitive factors, so generalisations should be avoided. Some of these factors depend on the modelling of the forest system, such as the timing of tree growth-associated carbon flows, the spatial level (e.g. stand or landscape) selected to model these flows, and the forest land use baseline. Others depend on LCA modelling parameters, particularly the choice of the time horizon for calculating impacts, the end-of-life assumptions and the time period for biogenic carbon storage.

To decrease uncertainty in climate impact assessments of biobased building materials, use of at least two metrics is recommended. At least one metric should allow assessment of emissions based on their timing, and applying long-term time horizons. Since accounting for non-traditional aspects significantly affects the results, it is also recommended that practitioners clearly state if and how these aspects are handled, and that multiple scenarios are studied with several possible methodological settings. Finally, it is recommended to account for technological changes when studying long-term climate impacts of building stocks, using dynamic models for processes in the future.

Keywords: *LCA, timber buildings, timber bridges, biobased building materials, dynamic LCA, climate change mitigation, building stock, scenario analysis, biogenic carbon*

SAMMANFATTNING PÅ SVENSKA

Irreversibel global påverkan på klimat och miljö måste undvikas och olika strategier som begränsar klimatförändringarna kan utnyttjas för att hantera denna utmaning. En betydande andel av de globala utsläppen av växthusgaser kan hänföras till byggsektorn i allmänhet och cementproduktion i synnerhet, och begränsningsstrategier söker alternativ till fossil- och mineralbaserade resurser, med mindre påverkan, som exempelvis en ökad användning av biobaserade material i byggandet. Livscykelanalys (LCA) har använts för att demonstrera klimatnyttan av denna ökning, men skogens komplexiteter i samband med biogent koldioxid skapar osäkerhet i resultaten då de som genomför LCA-studier traditionellt utelämnar viktiga nyckelaspekter.

Denna avhandling syftar till att öka förståelsen för effekterna av en ökad användning av biobaserade material för begränsning av byggandets klimatpåverkan i ett livscykelperspektiv. Forskningsfrågorna formulerades med fokus på att identifiera icke-traditionell LCA-metodik, samt att bedöma miljöeffekterna av en ökad användning av biobaserade material med redovisning av dessa aspekter på olika nivåer, gällande enstaka konstruktioner och byggnadsbeståndet som helhet. Den metodik som används är dynamisk LCA i kombination med data om skogskolbalans, med analyser av flera scenarier med olika metodologiska antaganden. Fallstudier med olika kännetecken användes, nämligen en byggnad, en bilvägsbro och en uppskattning av det svenska byggnadsbeståndet på lång sikt.

Resultaten bekräftar att en ökad användning av biobaserade material minskar klimatpåverkan av byggandet – en tydlig majoritet av de scenarier som analyserats för alla fallstudier resulterar i sänkt klimatpåverkan. Införandet av icke-traditionella LCA-aspekter påverkar resultatet, men förändrar inte att en ökad användning av biobaserade material resulterar i lägre långsiktig och kumulativ klimatpåverkan. Resultaten visar också att den maximala klimatbegränsningspotentialen endast nås genom att samtidigt införa andra tekniska lösningar med lägre klimatpåverkan. När det gäller LCA-metodik visar resultaten att antagandet att biobaserade byggnadsmaterial är klimatneutrala är en överförenkling eftersom deras klimatpåverkan beror på fallspecifika faktorer och därför bör inga generaliseringar göras. Några av dessa klimatpåverkande faktorer beror på modellering av skogssystemet i en dynamisk LCA; såsom när skogstillväxten antas börja i förhållande till avverkningen, den geografiska upplösningen för att analysera de biogena kolflödena dvs. som ett avverkningsbestånd eller på landskapsnivå och vad utgångsläget sätts till vid analys av skogens markanvändning. Andra faktorer beror på LCA-modellering, nämligen valet av integrerad tidshorisont för beräkning av klimatpåverkan, det antagna scenariot för avfallshantering och lagringsperioden för det biogena kolet i tillverkade produkter.

För att minska osäkerheten i bedömning av klimatpåverkan av biobaserade byggmaterial rekommenderas användning av minst en mätmetod som gör det möjligt att bedöma koldioxidutsläppen baserat på tidpunkten på dessa, samt att tillämpa mätvärden med långa tidsperspektiv. Redovisning av icke-traditionella aspekter har en betydande effekt på klimatpåverkan av biobaserade byggmaterial. Utförare av analyser rekommenderas därför även att redovisa hur dessa aspekter hanteras och att ställa upp flera olika scenarier och analysera dessa med flera olika metodologiska inställningar. Slutligen rekommenderas att ta hänsyn till den tekniska utvecklingen vid analyser av långsiktig klimatpåverkan av byggnadsbeståndet som genomförs med dynamiska värden för processer som äger rum i framtiden.

Nyckelord: *LCA, träbyggnader, träbroar, biobaserade byggnadsmaterial, dynamisk LCA, begränsning av klimatpåverkan, byggnadsbeståndet, scenarioanalys, biogent kol*

RESUMEN EN ESPAÑOL

Para evitar impactos irreversibles a nivel global, es necesario mitigar el cambio climático. Una parte significativa de las emisiones globales de gases efecto invernadero puede atribuirse al sector de la construcción y la producción de cemento. Entretanto, se busca implementar estrategias de mitigación de bajo impacto, tal es el caso de incrementar el uso de materiales de origen forestal. El análisis de ciclo de vida (ACV) se aplica con frecuencia para demostrar los beneficios climáticos de este incremento, pero las complejidades relacionadas con el bosque y el carbono biogénico crean incertidumbre ya que los autores normalmente omiten ciertos aspectos clave.

Esta tesis busca mejorar la comprensión de los efectos de un incremento en el uso de materiales de origen forestal en la mitigación del cambio climático en el sector de la construcción, bajo una perspectiva de ciclo de vida. Para ello se han formulado preguntas de investigación centradas en la identificación de los aspectos metodológicos no tradicionales del ACV que pueden afectar el resultado, así como en la evaluación de los efectos ambientales del aumento del uso de materiales biológicos en construcciones o en la construcción en existencia, mientras se toman en cuenta dichos aspectos. Los métodos aplicados incluyen el ACV dinámico en combinación con modelos del balance de carbón en el bosque, además del análisis de múltiples escenarios con diferentes configuraciones metodológicas y asunciones. Se utilizaron casos de estudio con diferentes características y sus respectivos productos equivalentes de referencia; un edificio, un puente para carretera pequeño y la construcción en existencia en Suecia a largo plazo.

Los resultados confirman que el aumento del uso de materiales de origen forestal disminuye el impacto climático de la construcción, ya que la gran mayoría de los escenarios analizados para todos los casos de estudio resultan en reducciones del impacto climático. La inclusión de aspectos no tradicionales del ACV ha influido en los resultados, sin afectar el hecho de que incrementar el uso de material biológico se traduce en menores impactos climáticos acumulados a largo plazo. Los resultados también muestran que el potencial máximo de mitigación climática sólo se alcanza mediante la implementación simultánea de otras tecnologías de bajo impacto. En cuanto a la metodología del ACV, la tesis ilustra que la hipótesis de que los biomateriales de construcción son neutrales respecto a sus impactos climáticos es una simplificación excesiva, y demuestra también que los flujos de carbono biogénico deben ser tenidos en cuenta. El balance de carbono de los materiales de construcción de origen forestal depende de factores relacionados con el sistema forestal que son sensibles las circunstancias del caso de estudio; por lo que no deberían hacerse generalizaciones. De dichos factores, algunos dependen de los modelos usados para simular el sistema forestal; tales como la contabilización del punto temporal de ocurrencia de los flujos de carbono biogénico, la perspectiva espacial para medir estos flujos y la línea de base trazada para el sistema forestal. Otros factores dependen del modelo usado para el ACV, como la elección del horizonte temporal integrado para el cálculo del impacto, el escenario de disposición final y el período de almacenamiento del carbono biogénico en los productos.

Para obtener conclusiones más robustas, se recomienda que los autores de estudios utilicen al menos un método adicional al GWP que les permita evaluar las emisiones de carbono basadas en el punto temporal de su ocurrencia, así como que se apliquen horizontes temporales a largo plazo en el uso de dichos métodos. Tener en cuenta los aspectos no tradicionales estudiados en esta tesis en estudios de ACV de materiales de construcción de origen forestal puede tener una influencia significativa en su impacto climático, por lo que se recomienda que los autores expongan claramente si estos aspectos se incluyen y cómo se incluyen. También se recomienda que se analicen múltiples escenarios con una variedad de configuraciones metodológicas alternativas. Por último, se recomienda tener en cuenta los cambios tecnológicos en los análisis a largo plazo de los impactos climáticos de la construcción en existencia, utilizando factores de impacto dinámico para los procesos que trascurran en el futuro.

Palabras clave: *ACV, edificio en madera, puente en madera, materiales de construcción de origen forestal, ACV dinámico, mitigación del cambio climático, construcción en existencia, análisis de escenarios, carbono biogénico*

PREFACE

The work this thesis is based upon has been carried out within the EnWoBio research project, a collaborative effort between KTH Royal Institute of Technology, RISE Research Institutes of Sweden, Luleå University of Technology and IVL, the Swedish Environmental Research Institute. My PhD project started in 2012, when the then SP Technical Research Institute of Sweden (now RISE) gave me an opportunity to stay in Sweden and start this journey. That opportunity changed my life, and I will never forget it. EnWoBio started for me after my licentiate seminar, giving me the opportunity to work part-time at KTH. This part-time leave from RISE allowed me to spend more of my time enjoying the life of a normal PhD student, which sky-rocketed my research and my motivation.

Most of the gratefully acknowledged financial support for my research came from the Swedish Research Council Formas (Project EnWoBio 2014-172) and the 'zero emissions building (ZEB)' research platform at RISE. Parts of the research work underlying this thesis have also been financed by other bodies, which I would also like to express my gratitude to. The study reported in Paper I was partly backed by the 'systems analysis' research platform at RISE. The work reported in Paper II was mostly funded by a Södra Skogsägarnas research grant. The renewable fuels and systems programme financed by the Swedish Energy Agency and the Swedish Knowledge Centre for Renewable Transportation Fuels (f3) provided support for the study described in Paper III. Funding by Träcentrum Norr (TCN) for the primary work for the case study described in Paper IV is also acknowledged. I would also like to thank the industrial partners who provided valuable input for this work in the form of case study data: Lindbäcks Bygg AB, Folkhem AB, Moelven Töreboda AB, Tyréns AB and Martinsons Group AB. Anna Esbjörnsson, Patrik Magnusson and James Ford, who are responsible for the "Urban Timber" project described in Paper II, also deserve a thankful mention.

It is now time to get a bit more personal, and I think I should start by thanking my former supervisor at SP, Dr. Per-Erik Eriksson. Per-Erik gave me a chance to work with his group, brought me coffee and bought me lunch on my first day, and then inspired me with his passion for climate action and wood construction. He recently moved on to saving lives in Africa while I sit at a desk, which I think is amazing. My second big thank you goes to my main supervisor Prof. Magnus Wålinder, who took me in as a PhD student in 2012 without hesitation. He was always there for me when I needed him and gave me some key advice, without losing his status as the cool boss. The third big thank you goes to Dr. Martin Erlandsson, my co-supervisor from IVL and probably the biggest name in LCA of construction in Sweden (I should know). His strict "devil's advocate" approach always improved my work substantially, but most inspiring was his unbiased environmental objectivity. Finally, I would also like to thank the two final additions to my supervisor roster; Dr. Johanna Berlin and Dr. Andreas Falk, who came in later but also provided valuable guidance and feedback. Johanna

also welcomed me into her group at RISE where my post-doctoral life awaits, which I look forward to.

The next group due personal thanks are my amazing colleagues and co-authors; you have been instrumental in my work in many ways. Thank you Frida and Gustav, my partners in the forest product dream team. Thank you my co-authors Joakim and Anna, whose support in some of my studies was extremely important. I am also very grateful to the Stockholm-Skellefteå-Helsinki EnWoBio gang, who made me feel part of something important while very much enjoying the ride. I must also mention my colleagues at RISE DKV67 who made me feel instantly welcome and were the best Swedish teachers, as well as my new colleagues at ETx and all their exciting projects I am dying to learn about. I would like to issue another thank you to my colleagues at KTH, who I was always glad to meet every Thursday for lunch and fika. Special thanks go to Magdalena Svanström, who went from inspiring teacher to very valuable co-author. Prof. Andreja Kutnar and Dr. Dennis Jones in Slovenia also deserve a place in this paragraph for allowing me to go on a wonderful short-term scientific mission there, among other valuable memories. Last but not least, I would like to thank my former bosses Karin Sandberg and Charlotte Bengtsson, as well as my former group at HS building and housing for their support.

Now all that are left are the most personal of acknowledgments, which I must write partly in Spanish. Quiero dedicarle esta tesis a mi madre Luz Marina, por haberlo hecho todo y dado todo para que yo sea lo que soy. A Claudia, mi fuente inagotable de amor, risa y compañía. A mis hermanos German y David, mi sobrino Samuel y mi ahijada Mariale; por alegrarme la vida. A mi madrina Martha porque tampoco estaría acá ni sería lo que soy sin ella. A mi familia Corredor por estar siempre ahí. A la naturaleza, que es mi Dios. I would also like to thank and send hugs to all my dear friends across the world in Bucaramanga, Bogotá, Gothenburg, Barcelona, California, Auckland and Stockholm. Finally, thank you Colombia for making me, and thank you Sweden for taking me in.

Diego Peñaloza

Stockholm, May 3rd 2017

LIST OF PAPERS

This thesis is based on the following appended papers, which are referred to in the text by the corresponding Roman numerals.

I. Røyne, F., Peñaloza, D., Sandin, G., Svanström, M., and Berlin, J. (2016). Climate impact assessment in LCAs of forest products: Implications of method choice for results and decision-making. *Journal of Cleaner Production* 116, pp 90-99.

II. Peñaloza, D., Erlandsson, M., and Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. *Construction and Building Materials* 125 (2016), pp 219-226.

III. Peñaloza, D., Røyne, F., Sandin, G., Svanström, M., and Erlandsson, M. The influence of system boundaries and baseline in climate impact assessment of forest products. Submitted to *the International Journal of Life Cycle Assessment* (March 2016).

IV. Peñaloza, D., Erlandsson, M., and Pousette, A. (2017). Climate impacts from road bridges: Effects of introducing concrete carbonation and biogenic carbon storage in wood. *Structure and Infrastructure engineering*. DOI: 10.1080/15732479.2017.1327545.

V. Peñaloza, D., Erlandsson, M., Berlin, J., Wålinder, M., and Falk, A. Future scenarios for decarbonisation of new building construction in Sweden: Effects of different technological pathways. Manuscript submitted to *Building Research and Information* (May 2017)

Work related to this thesis has also been presented in the following publications:

Sandin, G., Røyne, F., Peñaloza, D., Staffas, L., Svanström, M. (2015). The method's influence on climate impact assessment of biofuels and other uses of forest biomass. f3 report 2015:10. f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se

Peñaloza, D., Pantze, A., Erlandsson, M., and Pousette, A. (2016). Life cycle assessment of small road bridges: Implications from using biobased building materials. SBE16 Hamburg, International conference on sustainable built environment, conference proceedings pp 816-825.

Peñaloza, D., Eriksson, P. E. and Norén, J. (2013). Decreasing the carbon footprint of energy efficient buildings, what comes next? In Passivhus Norden 2013 Conference proceedings, available at www.laganbygg.se

Peñaloza, D., Norén, J. and Eriksson, P-E. (2013) Life cycle assessment of different building systems: The Wälludden case study. SP Report 2013:07. Borås: SP Technical Research Institute of Sweden. Available at: www.sp.se

SUMMARY OF THE APPENDED PAPERS

- **Paper I**

The traditional practices in climate impact LCAs of forest products were identified through a review of 101 studies in scientific publications. The traditional LCA practices in this context were identified in terms of how these studies handle a set of non-traditional aspects that have been recently highlighted as influential by several researchers. The consequences of following the traditional practices were then compared to those of accounting for the non-traditional aspects using two case studies of forest products with different characteristics; a short-lived biofuel and a long-lived timber building. The results indicate that LCA practitioners commonly exclude many of the non-traditional aspects identified. Moreover, the inclusion or exclusion of such aspects could significantly influence conclusions drawn from, and decisions based on, a life cycle climate impact assessment of a timber building.

Paper II

This paper presents a comparative LCA on effects of increasing the biobased material content in a building under scenarios with variations in four key assumptions: service life, end-of-life scenario, and timing of forest carbon sequestration and time horizon of the impact assessment. This involved calculating the climate impact of three building designs with equivalent functionality and varying content of biobased materials: a concrete design (0% biobased in mass), a conventional cross-laminated timber (CLT) structure (50% biobased in mass) and another CLT structure with higher biobased material content (69% in mass). The dynamic LCA method combined with forest carbon models is used in these case studies to account for the non-traditional aspects identified in Paper I. Increasing the biobased material content resulted in climate impact reductions in every scenario, but the differences between designs varied and were highly sensitive to all the assumptions explored. Moreover, the results suggest that using a longer time horizon than the commonly applied 100 years in global warming accounting will reduce dependency on the assumptions, and thus increase the results' robustness.

- **Paper III**

Starting from findings presented in Paper I, it accounts for non-traditional aspects using dynamic LCA and forest carbon models, but explores different ways to account for forest biogenic carbon flows; more specifically using spatial boundaries, time boundaries and a land use baseline. This was done through case studies of the following forest products with diverse service lives: an automotive biofuel (0 years), viscose textile fibers (2 years), methanol-based chemicals (20 years) and a CLT building (50 years). The difference in climate impact between the CLT building and concrete benchmark was found to be highly sensitive to aspects of the forest modelling, including geographical scale (stand, landscape or national), land-use baseline (zero baseline or natural regeneration) and timing of biogenic carbon flows. It was also found that long-lived products are less sensitive to the selected approach because the period that biogenic carbon is stored in the product is longer. Finally, the results validate the finding in Paper II that long time horizons reduce differences between results of climate impact assessments based on different approaches.

- **Paper IV**

In this paper, the focus moves to climate impact assessment of a small road bridge. Two alternative designs with massive timber and concrete slabs for a real-life case study were analyzed using dynamic LCA and forest carbon models to account for non-traditional aspects, as defined in Paper I. In addition, a non-traditional aspect for concrete structures was applied; the re-absorption of carbon dioxide by exposed concrete surfaces due to carbonation. The results show that accounting for non-traditional aspects affects results of assessments of timber road bridges (and their comparison with a benchmark) as substantially as it affects such assessments of buildings. They also show that the significance of concrete carbonation effects heavily depends on end-of-life assumptions, but it does not have a major effect on climate impact from a life cycle perspective. It was also found that the results are highly influenced by the timing of biogenic carbon sequestration in the forest, and an alternative approach to handle this uncertainty is proposed. The results presented in this paper also confirm the conclusion that long-term time horizons reduce uncertainties of results.

- **Paper V**

This final paper presents a substantial shift in methods and scope, moving from a single construction to the Swedish building stock, more specifically the potential to reduce climate impact by using biobased materials in new buildings. The paper presents an analysis of the climate impact of new building construction in Sweden, with eight scenarios featuring different development pathways related to the share of new buildings with high content of biobased materials. The scenarios also explore implications of different assumptions for other key variables, such as future developments regarding impacts from energy production and its effect on material manufacturing, the share of concrete buildings with reduced impact and the share of single family houses. Increasing the share of buildings with high contents of biobased materials reduced the cumulative climate impact in all scenarios studied. However, benefits of these increases varied substantially depending on the assumptions made for the other studied variables and the choice of metric to calculate climate impacts. The paper demonstrates that the dynamics of technological change are highly relevant for future studies of the building stock, and should not be omitted. It also demonstrates that implementation of all the available climate mitigation strategies simultaneously is required for optimal climate impact reduction.

LIST OF ABREVIATIONS

GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
HWP	Harvested wood products
LCA	Life cycle assessment
ISO	International Organisation for Standardisation
LCIA	Life cycle impact assessment
EPD	Environmental product declaration
PCR	Product category rules
CEN	European Committee for Standardisation
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
GWP	Global warming potential
CLT	Cross-laminated timber
HFA	Heated floor area

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1 Introduction

There is strong evidence that the global climate system is warming, and shifting towards patterns that have not prevailed for thousands of years (Field *et al.*, 2014). This change of the global climate is being driven by increases in radiative forcing; energy fluxes largely caused by soaring concentrations of carbon dioxide and other greenhouse gases (GHG) in the atmosphere (Ibid.). As human activity has been disturbing carbon cycles by increasing emissions of carbon dioxide since pre-industrial times, humans are the probably the primary causal agents of this climate change (Ibid.).

If current trends continue and GHG emissions keep rising, further warming and climate changes will come to pass, impacts that might only be limited by sustained and significant reductions in GHG emissions (Ibid.). It is estimated that humanity has already transgressed the climate change threshold for irreversible damage of planetary systems (Rockström *et al.*, 2009). This accumulation of evidence has given momentum to a global movement towards limiting the impacts of climate change. Recently, signatory nations of the United Nations Framework Convention on Climate Change reached a binding agreement to pursue all efforts to limit the global temperature rise to 1.5 degrees Celsius (United Nations, 2015), but keeping in mind an absolute limit of 2 degrees. Meanwhile, the Swedish government has established a goal to be climate neutral (i.e. cease net GHG emissions) by the year 2050 (Swedish Environmental Protection Agency, 2013).

The Intergovernmental Panel for Climate Change (IPCC) has defined climate change mitigation as human intervention to reduce sources or enhance sinks of GHG (Edenhofer *et al.*, 2014). Mitigation by GHG source intervention can be achieved by various means, such as shifting to renewable energy sources, adopting technologies associated with lower GHG emissions than current technologies and/or changing consumer behaviour. Given the urgency of the climate change problem and the irreversible nature of its impacts, all available mitigation strategies must be implemented, including all the necessary financial commitments. This urgency is pertinent for every industrial sector, but is particularly putting pressure on industrial sectors that strongly contribute to global GHG emissions.

1.1 The climate and the built environment

The building and construction sector is a major contributor to global GHG emissions. According to data from 2010 presented by the IPCC, around 18% of the global GHG emissions could be attributed to the construction sector (Edenhofer *et al.*, 2014). Furthermore, the construction sector has also been a major driver of the heightening of the climate change problem, as about 3% of the annual increases in GHG emissions in the last decade can be attributed to buildings (Ibid.). It is estimated that cement production activities in 2015 accounted for around 8% of the global carbon dioxide emissions, a production which has risen around 2.5-fold in recent decades, from approximately 1.6 Gton cement in 2000 to 4.1 Gton in 2016 (Olivier *et al.*, 2016). Although the cement industry is not expected to reduce its carbon intensity substantially in relation to other industrial sectors, the emissions per ton of cement can be brought down by around 50% without carbon capture and storage (SBT, 2015).

For these reasons, significant attention has been paid to climate change mitigation strategies in the built environment, paving the way for major global efforts. One example is the creation of a global standard for sustainable and resilient infrastructure, which was launched during the 2016 convention of the parties of the United Nations Framework Convention on Climate Change in Marrakech (GIB, 2016). Locally, the Swedish government has instituted "having a good built environment that contributes positively to the global environment" as one of Sweden's 16 environmental objectives (Swedish environmental protection agency, 2016).

From a life cycle perspective, the environmental impacts of buildings have been traditionally dominated by operational energy use (Buyle *et al.*, 2013). Hence, operational energy has been a low-hanging fruit when attempting to reduce buildings' environmental impacts. The focus on reducing energy use has stimulated the adoption of very low energy building codes, resulting in great achievements for climate impact mitigation, but reducing potentials for further improvements (Buyle *et al.*, 2013). Meanwhile, the transition to cleaner energy sources is also contributing improvements to the climate impact of the operational energy use. As a response, a shift towards a broader life cycle perspective in climate change mitigation of buildings has been observed. For example, life cycle indicators and a broader scope for climate impact reductions are starting to appear more clearly in certification standards for buildings (Anand and Amor, 2017). In Sweden, the building and housing agency has established an action plan to attain the national environmental objectives that includes strategies aimed towards the implementation of a life cycle approach to environmental impact reductions (Boverket, 2016). Due to this broadening in perspective, aspects other than energy use are becoming more relevant for climate change mitigation in buildings. These aspects are strongly related to the choice of materials, opening the door for alternative materials that offer reductions in carbon intensity.

1.2 Biobased building materials as climatic hopes

Increasing the proportion of materials manufactured from forest biomass in construction, referred to as biobased building materials in this thesis, is one of the alternatives that could potentially reduce GHG emissions. The main reasons for this are that low amounts of energy are used to manufacture biobased materials (relative to other materials such as concrete, gypsum or steel), and most of the energy used in their manufacture is generated from biobased by-products from their own value chain. In addition, manufacturing processes of common non-biobased building materials (e.g. calcination in the production of cement clinker) generate significant emissions. Manufacturers of common biobased building materials, such as timber or harvested wood products (HWP), and their associations usually emphasize the climatic benefits of biobased materials in their marketing strategies (Swedish wood, 2012). At the policy-making level, the European Commission (2000) has recently defined a set of criteria for bio-based energy wares to be considered sustainable, indirectly affecting HWPs due to the extensive use of bioenergy in their manufacturing process. Nevertheless, the climatic implications of the use of biobased materials have complexities that should not be neglected.

Forest ecosystems have complex relationships with GHG emissions and climate change. As already mentioned, enhancement of natural carbon sinks is one of two general strategies to mitigate climate impacts (Edenhofer *et al.*, 2014), but increasing forest biomass harvests could have unforeseen consequences for the state of carbon sinks, depending on various factors. Enhancement of carbon sequestration by forest sinks and protecting forests from deforestation are often mentioned in climate change mitigation strategies (Ibid.). In Sweden, forest protection is another of the 16 national environmental objectives (Swedish Environmental Protection Agency, 2016). Moreover, forests offer other ecosystem services which make them valuable in additional ways to carbon sinks, creating social movements with alternative visions of how forests should be managed. An illustrative example is the motion for a revision of the Swedish forest policy system by the Swedish Society for Nature Conservation (2014).

If not handled carefully, the use of biobased materials and forest protection could be conflicting objectives, which creates a certain level of uncertainty, especially for decision-making. This uncertainty and the complexities mentioned above could distort outcomes when GHG emissions and climate impact are assessed for products with biobased material content. Bridges and buildings, referred to in this thesis as construction works, are examples of these products. Consequently, environmental assessment methods such as life cycle assessment (LCA) should be applied to construction works with biobased building material content with these uncertainties and complexities in mind.

1.3 Aim and objectives

The overall aim of the studies this thesis is based upon was to create knowledge to enhance understanding of the effects that increasing the proportional use of biobased materials would have on climate impacts from the construction sector. This goal was formulated in more detail through the following research questions, each of which is followed by a short explanatory text and more specific objectives.

RQ1: What important aspects are missing from the common practices in climate impact assessment in LCA of biobased building materials and how much can they affect the outcome?

There are considerable complexities in the carbon flows and sinks related to forest ecosystems, and it is very likely that common climate impact assessment practices in LCA do not account for aspects that could be highly relevant. This research question prompted identification of these aspects and evaluation of the significance of their omission in the context of climate impact assessment, including comparisons with non-biobased benchmarks. RQ1 is addressed in Papers I and III, and to do so the following objectives were formulated:

- Carry out a literature review to identify aspects that could be relevant in climate impact assessment of biobased building materials, but are not commonly addressed by LCA practitioners in scientific publications.
- Use a building case study to illustrate effects of accounting for such aspects on outcomes of climate impact assessments and prospective comparisons with a non-biobased benchmark.

RQ2: What are the climate impacts or benefits of increasing the biobased material content in construction works?

Knowledge of shortcomings of current practices in climate impact assessments of biobased building materials would enable more robust methodology to obtain case study results accounting for relevant but neglected aspects. To address RQ2 case studies of construction works featuring alternative designs with varying biobased material contents were conducted, under a range of scenarios, in Papers II and IV. The following objectives were defined to answer RQ2:

- Compare the climate impact of three building designs with different proportions of biobased materials using a methodology that accounts for all relevant aspects identified when addressing RQ1.
- Apply this procedure in a comparison of two functionally equivalent bridge designs.

RQ3: What are the climate impacts or benefits of increasing the use of biobased materials in the Swedish building stock in the long-term future?

This final research question tackles the uncertainties associated with both larger-scale use of biobased materials in buildings and future technological developments. Future developments in energy production and emission factors could influence the magnitude of the benefits that could be obtained from using biobased materials in buildings as a strategy to mitigate climate impacts. The main objectives of the study to address RQ3 (reported in Paper V) were to:

- Create a model to estimate the current and future climate impacts of new building construction in Sweden.
- Use this model to assess the long-term climate impact of new building construction in Sweden under various development scenarios.

1.4 Guide for the reader

Chapter 1, which this guide concludes, introduces the subject of the thesis, and then describes the identified research gaps, the research questions that guided the underlying studies, and their aims and objectives. Chapter 2 presents a summary of the scientific background of the research, particularly recent findings and advances in life cycle assessment in construction, climate impact assessment of forest products, biogenic carbon accounting and assessment at the sector level. Chapter 3 outlines the methodological settings for the application of the chosen system analysis tools, including a description of the construction works case studies, the studied systems and the scenarios analysed for each studied system. This is followed, in Chapter 4, by a discussion of the research findings in relation to the research questions. Finally, Chapter 5 briefly presents the main overall conclusions, a set of recommendations for stakeholders, and prospective studies to continue the research.

2 Scientific background

This section describes recent findings related to the scope of the thesis to position the work and demonstrate its relevance to identified research gaps in the climate impact assessment of increasing the use of biobased materials, particularly harvested wood products, in construction.

2.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a systems analysis approach that allows assessment of the environmental impacts of a product or service during its life cycle, from the extraction of all the raw materials involved, through the manufacture of components and the product itself, and its service life, to its disposal or recycling processes (e.g. Baumann and Tillman, 2004). Impacts of all the intermediate processes and activities, such as transport, energy generation, maintenance and repair should also be included. Some of the strengths of the LCA approach lie in the systems perspective used to assess environmental impacts, avoiding challenges such as problem-shifting or assessments with limited scopes that omit key processes. All this should be done while relating the impacts of the product to a function through a functional unit, allowing direct comparisons.

International standards have established a generic procedure for carrying out an LCA, as described mainly in the International Organisation for Standardisation (ISO) standards 14040 and 14044 (ISO, 2006). It starts with definition of goals and scope, where the main methodological delimitations of the study (temporal, geographic, studied system) are established, including the functional unit. This is followed by a life cycle inventory (LCI), where data on all the relevant inputs and outputs to and from the studied system and ecosystems are inventoried and related to the functional unit. The third step is the life cycle impact assessment (LCIA), where the inventoried data are converted into environmental impacts grouped in diverse impact categories, each addressing a specific environmental issue. All data collected on emissions or natural resource use are translated into an equivalence unit that quantifies their environmental impacts using characterisation factors, which are specific for given substances and each impact category. Sums of the environmental impacts within the system boundaries for all selected impact categories are the overall results of the LCA. The final steps are interpretation of these results, derivation of conclusions and dissemination of recommendations related to the goals, in appropriate terms for the intended audience.

In the last three decades LCA has become increasingly influential in analyses of options and decision-making by public, private and academic stakeholders in increasingly diverse applications (Guinée *et al.*, 2011). Despite its rising popularity, LCA still requires further development. Indeed, a survey by Reap *et al.* (2008a, 2008b) identified and grouped 15 major aspects of LCA practice requiring improvement. Some of them are relevant to this thesis, including: the static nature of LCA in contrast to the dynamic nature of the environment and technology, the selection of appropriate temporal horizons for impact assessment, the need to consider alternative scenarios, and the need to define an appropriate “zero” baseline alternative. Despite its limitations, LCA is the only available approach that allows comparison between product systems over their whole life cycle so rather than replacing it, efforts should be directed to improve it and increase harmonisation (Finnveden, 2000).

2.2 LCA in construction works

Buildings and infrastructure projects have particularly complex product systems due to the diversity of their components, which generally include materials with diverse origins and fundamentally differing properties, weaknesses and functions. Thus, their life cycle stages and key processes differ significantly, making the application of LCA to buildings challenging. Despite these challenges, the urge to reduce environmental impacts of the construction sector has long prompted stakeholders to apply LCA to evaluate and improve the environmental performance of buildings and building materials (Buyle *et al.*, 2013), so the sector has a long history of applying LCA.

The environmental impact of construction works has been traditionally dominated by the use phase, which accounted for up to 90% of the total impact, but the implementation of low-energy designs has reduced this contribution (Buyle *et al.*, 2013; Weissenberger *et al.*, 2014). Consequently, the significance of material-related aspects of building designs such as manufacturing, maintenance and recyclability are becoming more relevant (Blengini and Di Carlo, 2010), and the focus of LCA researchers in the construction sector has shifted accordingly (Anand and Amor, 2017). For example, in a case study of a timber office building, Hereen *et al.* (2015) found that the choice of construction material was among the most influential parameters for the climate impact, and Takano *et al.* (2015) showed that material selection has substantial effects on LCA results even for conventional buildings, especially in the production and end-of-life stages. The relevance of the construction phase has also been highlighted by some researchers, where the difference between prefabrication and on-site construction is noteworthy, especially for wood products that are not always locally available (Takano *et al.*, 2014).

Due to the increasing attention to material choices, there have been numerous comparisons of building materials, which have resulted (among other things) in the development of environmental product declarations (EPDs). EPDs are documents that provide information about environmental impacts of products and construction works based on LCA methodology established by product category rules (PCRs; standards for EPD development applicable to a specific set of products). The European Committee for Standardisation (CEN) has provided PCRs for the construction sector through development and publication of a series of standards by its Sustainability of Construction Works Technical Committee. The LCA applied in these standards features a modular approach that facilitates material, component and building level integration (CEN, 2012a; CEN, 2012b). In this modular approach, the life cycle of a building is divided into three life cycle stages (A to C), as illustrated in Figure 1. The standards propose distribution of data regarding the life cycle stages into different information modules, with standardised treatment of life cycle impacts, mainly for communication of results (CEN, 2012a; CEN, 2012b).

<table>
<tr><th colspan="15">Building assessment information</th></tr>
<tr><th colspan="14">Building life cycle information</th><th>Supplementary information beyond the building life cycle</th></tr>
<tr><th colspan="3">Product stage (A1-A3)</th><th colspan="2">Construction stage (A4-A5)</th><th colspan="5">Use stage (B1-B7)</th><th colspan="4">End of life stage (C1-C4)</th><th>Benefits and loads beyond the system boundary (D)</th></tr>
<tr><td rowspan="3">Raw material supply - A1</td><td rowspan="3">Transport - A2</td><td rowspan="3">Manufacturing - A3</td><td rowspan="3">Transport - A4</td><td rowspan="3">Construction, installation process - A5</td><td>Use - B1</td><td>Maintenance - B2</td><td>Repair - B3</td><td>Replacement - B4</td><td>Refurbishment - B5</td><td rowspan="3">De-construction/demolition - C1</td><td rowspan="3">Transport - C2</td><td rowspan="3">Waste processing - C3</td><td rowspan="3">Disposal - C4</td><td rowspan="3">Reuse-, recovery-, recycling potential - D</td></tr>
<tr><td colspan="5">Operational energy use - B6</td></tr>
<tr><td colspan="5">Operational water use - B7</td></tr>
<tr><th colspan="3">Upstream processes</th><th colspan="2">Core processes</th><th colspan="9">Downstream processes</th><th>Inclusion optional</th></tr>
</table>

Figure 1 *The life cycle of a building according to the CEN 15804 standard series (CEN 2012a)*

Anand and Amor (2017) also identified a set of challenges and opportunities for improving LCA of buildings practice. Of these challenges, a lack of both harmonised practices for selecting service life assumptions and system boundaries is particularly relevant to this thesis. A building's service life varies considerably in reality, and since service life assumptions have substantial importance for results of building LCA results they should be carefully considered (Grant *et al.*, 2014). Due to the relatively long service life of buildings, their end-of-life processes occur in a distant future, so there are substantial uncertainties about them and requirements for additional measures such as scenario analysis (Sandin *et al.*, 2014). Moreover, further normalisation of practices is needed for modelling buildings' end-of-life processes and scenarios (Bovea and Powell, 2016). Finally, even small changes in system boundaries may have significant consequences, due to the complexity of building materials' product systems, so secondary effects should be carefully considered when setting the boundaries (Ylmén *et al.*, 2017).

2.2.1 LCA of bridges

In addition to the strong attention to the analysis of buildings, LCA has also been used to assess the environmental impacts of other construction works, such as roads and bridges (Cabeza *et al.,* 2014). Bridges do not have an energy-intensive operational phase, so the material manufacturing and maintenance life cycle stages are the main contributors to their climate impact, although the uncertainties of all construction works' end-of-life processes must also be addressed (Bouhaya *et al.*, 2009). Results obtained by Pang *et al.* (2015) confirmed that operation and maintenance can contribute significantly to endpoint LCA results for bridges. Most LCA studies of bridges have focused on steel and concrete structures, since wood cannot be used for heavy-duty superstructures. Moreover, among the few previous studies to assess wooden bridge structures, none has considered aspects specific to biobased materials. The most relevant study was a comparison of timber and steel-and-concrete bridge structures by Hammervold *et al.* (2009), whose main finding was that the selection of functional unit has considerable effects when comparing designs. It should also be noted that LCA results for bridges are case-specific and generalisations should be avoided, due to the complexities of their superstructures (Du and Karumi, 2014). A strategy for identifying ways to mitigate the climate impact of a concrete bridge superstructure design has been presented by Krantz *et al.* (2016), involving the integration of LCA with Building Information Modelling and other construction management approaches, but they did not extend this strategy to comparisons with alternative designs.

2.3 Climate impact of biobased materials

Increasing the use of biobased materials in buildings is regarded as a climate mitigation strategy, since buildings with high contents of biobased materials normally have lower estimated climate impacts than corresponding buildings with low contents (Weiss *et al.*, 2012). However, there have been significant differences in both methodology and results of several studies that have quantified the climate impact of forestry operations and harvesting of forest biomass used to generate biobased materials applied in LCAs (Klein *et al.,* 2015). Moreover, Lewandowska *et al.* (2008) showed that location-specific aspects of forest product systems can significantly affect LCA results.

The life cycles of biobased materials include forest harvesting; a process that features biogenic carbon flows that adds complexities when climate impacts are studied. Biomass harvesting activities might affect forests' carbon balance, and thus the climate through disturbance of exchanges between their carbon sinks and the atmosphere. Carbon exchanges in the forest have previously been integrated with emissions from forest operations to obtain net carbon balances of timber and bioenergy production (Kilpeläinen *et al.*, 2011). Results have shown that changes in forest carbon fluxes exceed emissions associated with forestry operations, and thus should not be neglected (Kilpeläinen *et al.*, 2011). Kilpeläinen *et al.* (2016) subsequently applied a similar approach to estimate effects of using timber as a substitute for fossil-intensive materials, such as concrete, in construction. Clearly, evaluation of the life cycle impacts of biobased materials requires consideration of certain aspects that are irrelevant to impacts of other materials, but current LCA standards do not provide guidance for handling those (Pawelzik *et al.*, 2013). These aspects are discussed in detail in this sub-section, especially those addressed in Papers I-IV.

2.3.1 Climate neutrality of biobased materials

When assessing climate impact of forest products, it is common among standards and practitioners to assume climate neutrality. It is argued that the carbon sequestered by the trees through photosynthesis (referred to as biogenic carbon), is equivalent to the carbon released back to the atmosphere at the end-of-life of the product. Due to this equivalence both flows equal each other out in climate impact assessment, an approach that has been challenged for some years (Johnson, 2009). For example, Wiloso *et al.* (2016) demonstrated that accounting for biogenic carbon flows in life cycle inventories of forest products can substantially affect their climate impact, and that assuming carbon neutrality introduces biases may lead to erroneous decisions. It has also been demonstrated that biogenic carbon dioxide indirectly influences methane oxidation rates (Muñoz and Schmidt, 2016).

The validity of the climate neutrality assumption depends on the net carbon balance of forest carbon sinks when forest biomass is exploited, and thus the spatial and timeframes used to estimate this carbon balance. Eliasson *et al.* (2013) found that the long-term forest carbon balance would remain stable at landscape level, even with more intense harvesting in a Swedish forest. Similarly, based on statistics and previous studies, O'Sullivan *et al.* (2016) argue that the stability of European forest carbon stocks supports the carbon neutrality assumption for forest products, and highlight the importance of site-specific data and traceability of forest biomass in products and its geographical origin. In contrast, results of a stand-level analysis by Holtsmark (2013) suggest that increasing harvests of forests would lead to a permanent increase in atmospheric carbon dioxide concentration, and notes that assessing effects of a single harvest rather than multiple harvests leads to fundamentally different results. However, Cherubini *et al.* (2013) argue that the results obtained using a landscape and stand approach can be reconciled, obtaining similar results for the climate impact of bioenergy using both approaches.

*2.3.2 The land use baseline **in** the forest*

The choice of land use baseline in LCA has received significant attention in recent years. After reviewing relevant literature, Soimakallio *et al.* (2015) highlighted the importance of establishing a baseline when calculating environmental impacts using LCA instead of using inventories of absolute emissions, identified four common approaches and concluded that "The most coherent baseline for human-induced land-use in ALCA is natural regeneration". Brander (2016) challenged this, and several other points of those raised by Soimakallio *et al.* (2015), arguing that natural regeneration is not conceptually appropriate for attributional LCA. Soimakallio *et al.* (2016) subsequently replied to the comments by Brander, essentially noting that "land occupation (i.e. postponing natural regeneration) causes environmentally relevant physical flows, and their impacts need to be considered for any ALCA in which land use is a resource flow, in order to avoid misleading results". It should be noted that natural regeneration in this context refers to conditions if land used for forest harvesting was abandoned and converted to a natural forest, not to the practice of allowing felled stands to regenerate without further intervention in modern forestry rotations. The choice of land-use baseline is particularly important for biobased materials, because estimated effects of biomass harvesting on the forest carbon balance and other phenomena are significantly influenced by the baseline or reference situation used in their quantification. This is probably defined most often using the 'business as usual' approach (i.e. continuation of current practices and conditions). In this thesis, both 'business as usual' and 'natural regeneration' as defined by Soimakallio *et al.* (2015) are considered.

2.3.3 Biogenic carbon storage in products

Temporary storage of biogenic carbon in biobased materials has extensively demonstrated climate benefits (Brandao *et al.*, 2013). Thus, the amounts (or fractions) of biogenic carbon stored in products or released into the atmosphere, and the timeframes involved have been identified as key issues for products made from forest biomass. Nevertheless, despite requiring (to some extent) their inclusion in life cycle inventories, standards and guidelines usually ignore climate impacts related to the forest carbon cycle and biogenic carbon storage (Åhlgren *et al.*, 2015). Temporal differentiation of background and foreground processes can be highly important to address this deficiency in climate impact assessment protocols, particularly for forest products (Pinsonnault *et al.*, 2014). However, although several methods to account for these storages are available, development of a consensus regarding the most appropriate methods to use has been hindered by a need for value judgements when defining a time horizon (Brandao *et al.*, 2013). In recent years, the sequestration and storage of biogenic carbon have been identified as critical aspects for climate impact assessment of biobased materials, further highlighting the lack of consensus about the optimal approach and metrics (Pawelzik *et al.*, 2013). Pawelzik *et al.* (2013) also highlighted the challenge of obtaining site-specific data for estimations of changes in soil organic carbon. It should also be noted that temporary storage of biogenic carbon in biobased materials does not always result in climate benefits. In combination with certain choices of baseline, the potential benefits obtained also depend on the storage period, the rotation period of the feedstock biomass and the time horizon assumed (Guest *et al.*, 2013).

2.4 Climate metrics and biogenic carbon accounting

The choice of metric to measure climate impact has been intensively debated recently. Cherubini *et al.* (2016) concluded that current approaches using a single metric fail to capture the complexity of the climate system, which could lead to implementation of suboptimal mitigation strategies. Similarly, Levasseur *et al.* (2016) argue that in an LCA context several complementary metrics and time horizons should be used to enhance the robustness of climate impact assessment. Different standards for carbon footprints recommend different approaches for biogenic carbon accounting, and although this accounting is not mandatory, these differences have been shown to heavily influence outcomes of assessments (García and Freire, 2014; Tellnes *et al.*, 2015).

Global warming potential (GWP) is the metric that is traditionally used to assess climate impact in LCA, a simplified index of the approach developed by the Intergovernmental Panel on Climate Change (IPCC) (Myhre *et al.*, 2013). GWP is defined as “the time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2” (Ibid.), i.e. the amount of heat a substance traps in the atmosphere relative to carbon dioxide. However, the application of GWP in LCA is usually static, as it does not account for the timing of the emissions (Levasseur *et al.*, 2010). Furthermore, since carbon flows in forests are dynamic, it has been pointed out that GWP is not an adequate metric for climate impact assessment of forest products (Brandao *et al.*, 2013; Cherubini and Tanaka, 2016).

Helin *et al.* (2013) argue that in order to assess forest products’ climate impact objectively, the chosen approach should account for the timing of GHG flows, properly define a forest reference situation and allow use of different time frames. A method proposed in early stages of LCA research by Moura-Costa and Wilson (2000) to account for carbon sequestration involved calculating an “equivalent time” during which the carbon sequestered must be stored in order to offset a certain amount of emissions. However, Vogtländer *et al.* (2014) argued that only simultaneous global growth of forest land and use of wood can contribute to an increase in carbon sequestration in products and proposed a method to allocate these increases to a single product. An approach regarded as complementary to calculating GWP values, proposed by Jørgensen *et al.* (2014), involves estimating effects of temporary carbon storage in biomaterials on atmospheric GHG concentrations and calculating the ‘climate tipping potential’ (the impact of emissions divided by the ‘capacity’ of the atmosphere to absorb the impact without exceeding a short-term target level).

Another metric for accounting for biogenic carbon flow is GWP_{bio}, which integrates biogenic carbon exchanges in forest with the global carbon cycle (Cherubini *et al.*, 2011). Its calculation involves use of an unmanaged forest baseline, so all harvesting activities would create a temporary loss of some of the forest’s biogenic carbon pool. The method was later expanded to account for time delays between carbon sequestration in the forest and a pulse emission of the carbon after a storage period, resulting in a set of characterisation factors that can be applied to biogenic carbon emissions for different rotation and storage periods, with a fixed time window and baseline approach (Guest *et al.*, 2013). Helin *et al.* (2015) applied the GWP_{bio} approach using a region-specific model to predict changes in forest carbon stock, with the same unmanaged forest as a baseline. They obtained somewhat different characterisation factors than previous studies, suggesting that climate neutrality should only be assumed for long-lived biobased materials. More recently, the method was further expanded to account for the emissions caused by alterations in biomass decomposition processes resulting from increases in biomass harvesting (Liu *et al.*, 2017).

2.4.1 Dynamic LCA

Dynamic LCA is an approach proposed by Levasseur *et al.* (2010) where the timing of GHG emissions or sequestration is considered when calculating their climate impacts with respect to a fixed time horizon. The magnitude of each pulse emission is assessed during the period between its occurrence and the chosen time horizon. Figure 2 illustrates the concept behind Dynamic LCA, where the magnitude of the impact is obtained by integrating the area under the radiative forcing curve during the interval between the year of occurrence (year zero) and the given time horizon. The method was originally intended to address the limitation of the static nature of LCA, and provide consistency between the time boundaries of an LCA and the time horizon of the climate impact assessment (Levasseur *et al.*, 2010). The problem with using a fixed time horizon of 100 years lies in the fact that the long-term consequences of processes, for example biogenic carbon sequestration during forest growth, cover much greater time spans.

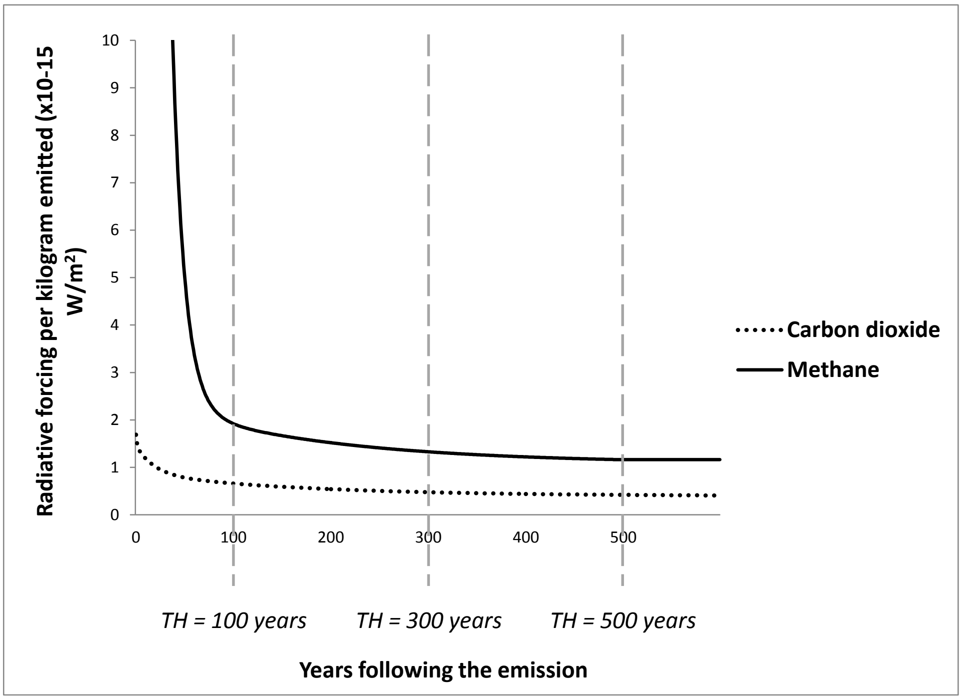

Figure 2 *Radiative forcing caused by a 1 kg pulse emission of carbon dioxide or methane at time zero over three time horizons (TH)*

The dynamic LCA method was subsequently used to estimate the climate effects of temporary carbon storage, in a case study where biogenic carbon flows were included in the life cycle inventory of the dynamic LCA of a wooden chair (Levasseur *et al.*, 2012). The time gap between sequestration and emission of the biogenic carbon stored increases the impact by the sequestration, and when both impacts are superposed the outcome is a net climate benefit for long-term storage of carbon in products. Fouquet *et al.* (2015) also applied Dynamic LCA to investigate temporally dynamic climate aspects of buildings such as biogenic carbon flows and changes in energy supply in a case study of a single-family house in France. They found that rankings of design alternatives remained the same, but the gaps between biobased and non-biobased alternatives were increased by accounting for biogenic carbon storage.

2.4.2 Including forest carbon flows in LCI

Challenges that practitioners face when implementing any of the described metrics are modelling the forest carbon balance and integrating the resulting model with a life cycle inventory. Kilpeläinen *et al.* (2011) and Kilpeläinen *et al.* (2016) successfully integrated forest carbon balances with traditional LCA, but without accounting for timing of either emissions or biogenic carbon storage. Gaboury *et al.* (2009) used complex carbon models to estimate the forest carbon balance of afforestation projects in comparison to a natural forest baseline under different scenarios. They combined these models with LCA to assess the impact of afforestation and provided recommendations to maximize the mitigation benefits, but did not account for the timing of emissions and carbon storage effects. More recently, a parametric model presented by De Rosa *et al.* (2017) introduced a simplified approach to obtain time-explicit carbon fluxes for the life cycle inventory of forest products, which can be easily implemented by practitioners in any of the climate metrics discussed.

2.5 Climate impact assessment at broader levels

So far, this section has focused on climate impact assessment at the material or building level using LCA. However, climate impacts can also be assessed for broader systems, such as a country, an industrial sector, a landscape or a region. For example, carbon flows can be accounted specifically for biobased materials in a given country, and using different approaches with quite different outcomes depending on the type of data used, e.g., generic data from IPCC guidelines or case-specific data that require substantial collection efforts (Jasinevičius *et al.*, 2017). Others have used a country-level scope to assess effects of increasing the use of biobased materials. Notably, consequences of increasing use of harvested wood products in the USA in terms of GHG emissions were explored by Nepal *et al.* (2016), who found it would provide net carbon savings in the long-term. This approach has also been used to estimate net carbon emissions of forest products in Sweden, including the net carbon balance in the forest. For this, practical aspects such as the intensity of harvesting practices or location and methodological choices such as reference situation and spatial perspective have proven highly influential for the outcome (Lundmark *et al.*, 2014; Cintas *et al.*, 2015).

Environmental effects can also be assessed for a given building stock. For example, Holck-Sandberg and Brattebø (2012) used material flow analysis to estimate future energy flows of the Norwegian building stock. They concluded that assumptions such as the energy source used for electricity generation and the approach for calculating future emissions are highly relevant. LCA can also be combined with other approaches to obtain more robust models, mainly by using case-specific LCA data to make generalizations for certain material or energy flows. For example, Pauliuk *et al.* (2013) used this methodology to identify potential pathways towards the attainment of long-term climate targets of the Norwegian building stock. Suter *et al.* (2017) also used material flow analysis, in conjunction with LCA-based indicators, to evaluate changes in GHG emissions associated with increases in wood use in Switzerland, and concluded that replacement of energy-consuming materials provides the highest environmental benefits. In a contrasting approach, Guest and Strømman (2014) illustrated the dynamics of biogenic carbon related to HWPs using material flow analysis, and proposed a method to attribute these impacts to a single product, potentially in an LCA context.

All the cited broad-level studies assessed, to some extent, carbon flows and climate impacts under future scenarios, but dynamic displacement factors were only used in one of them. Thus, emissions or impacts avoided by using one technology instead of a benchmark throughout the covered periods implicitly remained static in the other studies. In the exception, Holck-Sandberg and Brattebø (2012) accounted for technological change in their model, using dynamic emission factors for some processes. Their results demonstrated that technological development has dynamic effects on emission and displacement factors, which should not be ignored in such models.

3 Methods

This section describes the methods used to address the research questions expressed in section 1.3. The overall approach applied in the studies reported in Papers I-V was to use scenario analysis to test effects of different methodological choices and assumptions on the climate impact assessment of biobased materials at two levels: construction works and building stock.

3.1 Literature review

A literature review was carried out to identify aspects that could affect the climate impact assessment of forest products, but were not traditionally addressed in LCA studies by practitioners, in the context of scientific publications. For inclusion in the review, the papers had to:

- Be identified in a search with the Boolean string "('forest' OR 'wood') AND ('life cycle analysis' OR 'life cycle assessment' OR 'LCA')".
- Address products that were at least partly made from forest-based biomass.
- Have their main focus on environmental assessment of materials or products, not product development.

The review analysed how the selected papers handled key aspects (identified from the literature and summarized in Figure 3) of forest products' climate impacts. This enabled identification of a set of common practices in climate impact assessment of forest products, based on observed trends in practitioners' handling of these key aspects. It also allowed identification of aspects that could affect the outcome of such studies but were neglected in common practices.

3.2 Case studies and studied systems

After identifying the non-traditional but highly relevant aspects of climate impact assessment of forest products, their influence was analyzed in a series of case studies. These case studies focus on various parts of production systems, and cover all three of the research questions in different ways. This subsection introduces the case studies, providing a short summary of their most relevant features for the system modelling in the appended papers.

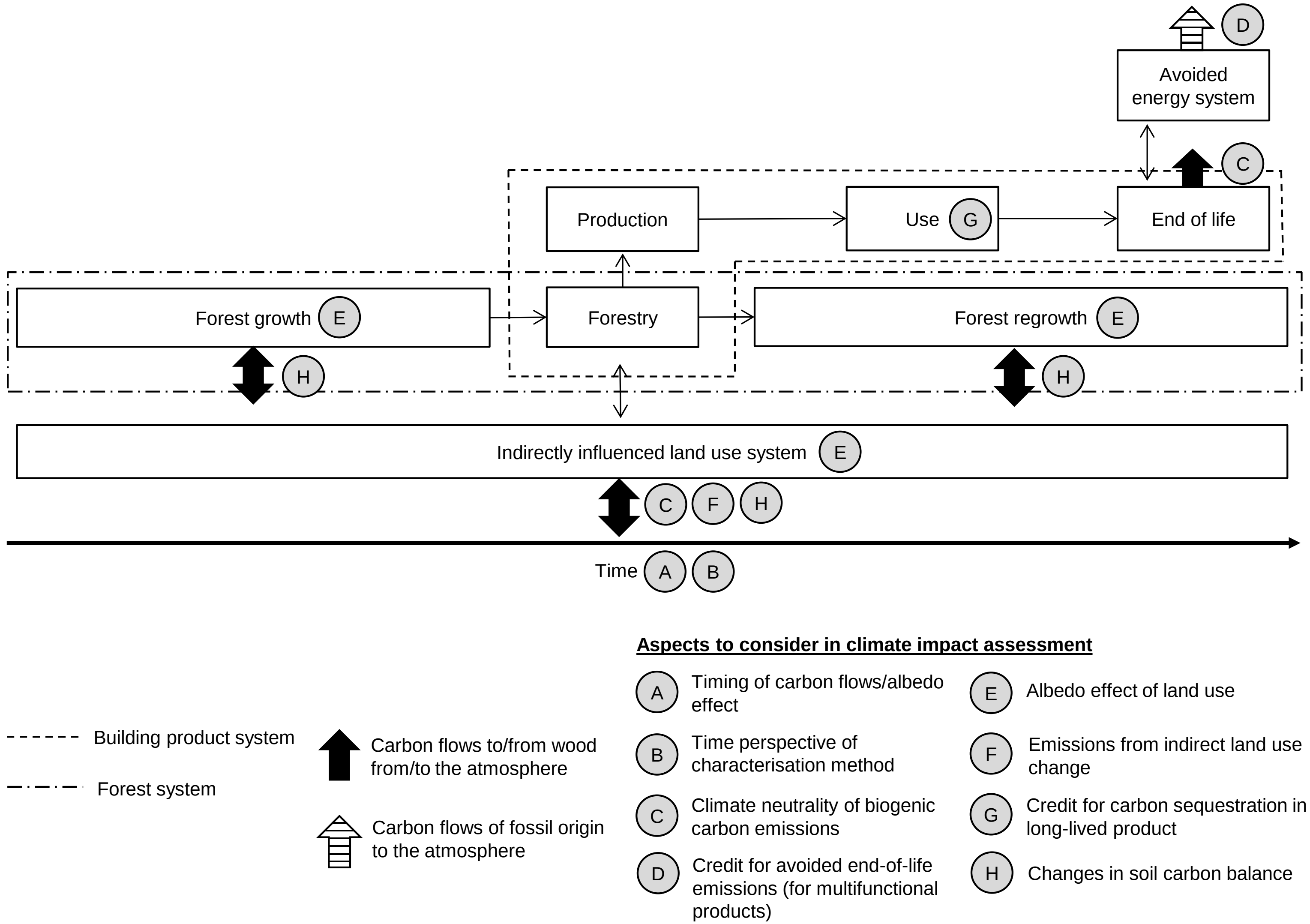

Figure 3 *Generic production system of a forest product, featuring aspects that were identified as most relevant for climate impact assessment of biobased building materials.*

3.2.1 CLT-based building

Case studies reported in Papers I, II and III focused on production of a conventional timber building. 'Conventional' here refers to buildings constructed by one of the most well-established timber building systems in Sweden, which is commonly used and can be considered state-of-the-art. The building system was developed by the company Martinsons AB, and has been subjected to LCA by several authors (Kuittinen *et al.*, 2013; Larsson *et al.*, 2016; Kurkinen *et al.*, 2015). The most important characteristics of this building system are its structural use of massive plate elements made of cross-laminated timber (CLT) and a significant degree of prefabrication in the supplier's factory, from where plate elements are transported to and assembled at the building sites. This system was chosen because the resulting buildings have higher biobased material contents than buildings constructed using any of the other commonly applied timber building systems in Sweden. A summary of the most relevant design features of this and the other systems considered in the studies is presented in Table 1. In each case study the system was adapted to fit the context and goal of the study with respect to location, number of floors, exclusions, living area, façade system, assumptions and overall system boundaries, but the design concept was basically the same. The appended papers provide further information.

Table 1 *Summary of design characteristics of the building systems addressed in the case studies.*

Key design features	CLT-based building	CLT with increased biobased content	Concrete benchmark
Literature reference(s)	Kuittinen *et al.* (2013), Peñaloza *et al.* (2013)	Esbjörnsson *et al.* (2014)	Peñaloza *et al.* (2013), Paper II, Kurkinen *et al.* (2017)
Foundation and ground slab	Concrete and expanded polystyrene	Concrete and expanded polystyrene	Concrete and expanded polystyrene
Structural elements	Cross-laminated timber (CLT)	Cross-laminated timber (CLT)	Concrete
Insulation in walls and roof	Mineral wool	Cellulose fibre insulation	Mineral wool
Roof elements	Glulam and sawn timber	Glulam and sawn timber	Concrete
Coverings and details	Plywood, sawn timber and gypsum board	Oriented stranded board, plywood and sawn timber	Gypsum board
Extras	None	Sprinkler system (PVC pipes)	None
Manufacturing of elements	In factory	In factory	On-site

All the studied building designs comply with the Swedish passive house standard (Boverket, 2012) to reduce the dominance of the operational energy's contribution to the buildings' climate impact, so changes related to the material production and end-of-life stages could be studied more closely. The inventory data used for material production processes in the building case studies were based on Ecoinvent 2.0 data for material and energy flows, with upstream process adaptations to Swedish practices based on communications with stakeholders, literature data and knowledge of the regional practices of the HWP industry. The most important modifications concerned the inventory data for forestry operations (Berg and Lindholm, 2005), the amounts of adhesive used per cubic meter for CLT and glulam, the exclusive use of bioenergy from waste for manufacturing HWPs, and the use of updated and country-specific data for electricity and heat supplies. In all cases, on-site construction and demolition activities were assumed to be powered by diesel, and unmodified data from Ecoinvent were used for transport and material disposal processes. End-of-life scenarios varied slightly in each study, depending on the context.

3.2.2 CLT building with increased biobased material content

Another timber building concept was considered, called 'Increased bio' in Paper II. The concept, formulated in the 'Urban timber' research project (Esbjörnsson *et al.*, 2014), was essentially a development of the CLT-based building system, involving replacement of mineral-based insulation and coverings with biobased alternatives such as cellulose-based insulation and oriented stranded board. Due to the removal of the gypsum board, a sprinkler system was needed to comply with fire protection regulations. Consequently, the manufacture of the sprinkler system was accounted for in the study. This system was chosen as it represents a functionally-equivalent development of the established CLT-based building system that increases the content of biobased materials from 50% to 69% by mass. Thus, it enabled analysis of building-level effects of increasing the use of biobased materials. Design features of this system are summarized in Table 1 , and in more detail in Paper II and its supplementary material.

3.2.3 Concrete building benchmarks

In LCA studies a benchmark is usually assessed following the same methodology as the studied product for comparative purposes. Thus, in all three case studies of buildings a concrete benchmark with a minor content of biobased materials was also studied (Papers I-III). All the concrete designs used as benchmarks were based on conventional concrete systems, and relevant data were mostly obtained from previous, published studies. However, the specifications of the concrete benchmark varied considerably as they were adjusted in accordance with the context and objectives of each study. The specifications of the design used in the study reported in Paper I correspond to those presented by Peñaloza *et al.* (2013) and Kuittinen *et al.* (2013). Meanwhile, designs used in the studies presented in Paper II and Paper III are partly based on the concrete building system presented in Kurkinen *et al.* (2015), with modifications concerning the service life of the building (and therefore maintenance assumptions), the concrete formulations and the data source for the manufacturing of the cement, obtained from EPDs published by Nordic cement manufacturers. Further information about these modifications can be found in the supplementary material for Papers II and III.

3.2.4 Small road bridge

The case study reported in Paper IV concerns a small bridge in Åstorp, a municipality in southern Sweden, along the road Malmövägen. This bridge was rebuilt in 2014, keeping the original foundations and replacing only the concrete slab. The new bridge consists of a superstructure with simple supports, and a span of about 15 meters for two lanes and load-bearing capacity class BK-1, according to the Swedish Transport Administration's classification system. As part of the research project that provided data for the case study, an alternative for the new bridge slab was designed. This alternative design had an equivalent functional road area, a pre-stressed wooden slab in glued laminated timber, increased height and pressure-impregnated unpainted wooden panel coverings, coated on the side and painted on the underside. An equivalent service life of 80 years was assumed for both alternatives.

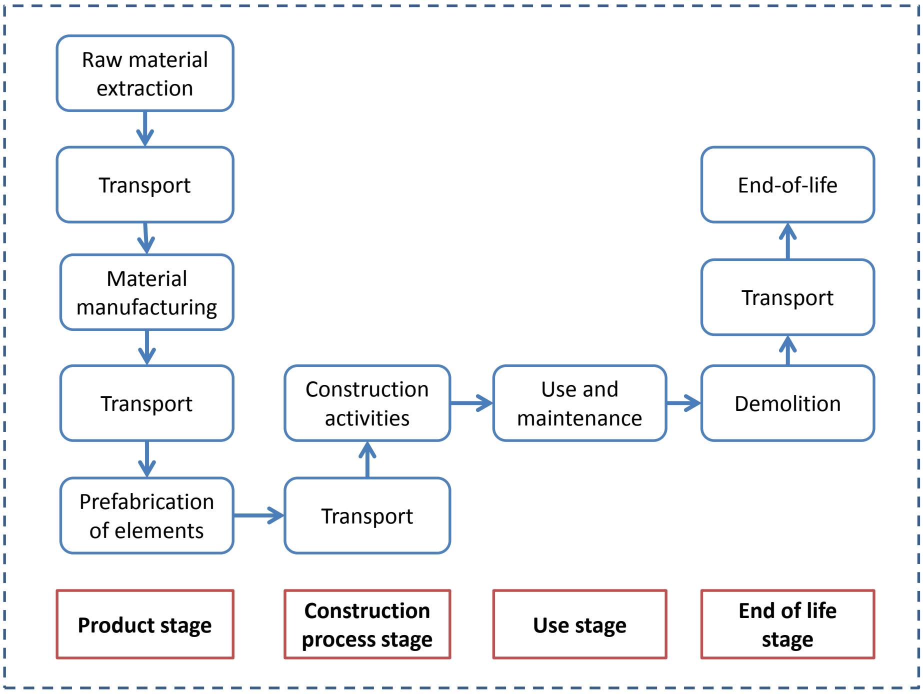

Figure 4 *Boundaries of the systems considered in the case study reported in Paper IV.*

There are two key differences between the two designs. First, the railings and expansion joints have different dimensions, which affect the maintenance. Due to the uncertainties related to the maintenance a sensitivity analysis was performed using worst-case scenario assumptions for maintenance of the wood design. The second is the level of prefabrication; while the wood alternative is prefabricated and requires additional transport, the concrete alternative was cast in-situ. Figure 4 shows the boundaries of the systems considered in the case study reported in Paper IV, and more specific information about the bridge designs and the maintenance assumptions can be found in the appended paper. The inventory data pertaining to material manufacturing, transport, construction activities, demolition and disposal processes were similar to data used in the building-level case studies, as described in section 3.2.1.

3.2.5 Swedish building stock

In the study reported in Paper V, the scope of the system analysis was broadened to national building stock level. Based on historical statistics, a model to estimate the yearly total amount of heated floor area (HFA) built in Sweden for the coming 100 years was constructed. Based on these estimations, the total amount of new building materials required to supply this heated area was obtained. For this, eight building typologies were defined to form the Swedish building stock in proportions or market shares based on official statistics, proportions that changed over time depending on the assumptions for each scenario. These typologies were defined according to the availability of LCA data and other relevant statistics. The parameters differentiating the typologies were the size of the dwellings, predominant building material in the structures and building concept. A summary of the typologies chosen is presented in Table 2.

***Table 2** The eight building typologies used to model the Swedish building stock in Paper V.*

Typology	Description	Data reference
1-2 family house	2-storey house considered representative for Nordic single houses.	Dokka *et al.*, (2013)
Prefabricated volume elements	Modular prefabricated volume elements transported and mounted at the site.	Peñaloza *et al.* (2013)
Massive elements, CLT	Massive timber CLT element structure	Peñaloza *et al.* (2013)
Column-beam, LVL	Structure of LVL and glulam beams and columns, including a concrete staircase.	Peñaloza *et al.* (2013)
Traditional on-site casted concrete	Modern ZEB building design.	Sinha *et al.* (2016)
VST concrete system	in-situ cast concrete in prefabricated remaining formwork based on cement-based particle boards	Liljeström *et al.* (2015)
Low-impact concrete	A concrete building system with several climate mitigation strategies implemented.	Kurkinen *et al.* (2015)
Steel	Due to the lack of studies in Sweden, a case study from China was used as a proxy.	Su and Zhang (2016)

Data from LCA studies and databases were used to obtain the yearly GHG emissions from the systems using emission factors for the included processes, mostly from EPDs and Ecoinvent 3.1. The processes included in the assessment are shown in Figure 5. Some of these emission factors changed over time, as the aim of the study was to capture effects of technological development in long-term assessments of building stock climate impacts (see section 3.5). Moreover, material-specific phenomena such as biogenic carbon storage effects and concrete carbonation were accounted for, so one of the climate metrics used in Paper V was cumulative radiative forcing, calculated using dynamic characterization factors. In contrast, a steady state was assumed for the forest, based on previous indications that increasing the intensity of forest harvesting would have net forest carbon benefits (Cintas *et al.*, 2015, Eliasson *et al.*, 2013). Consequently, each unit of carbon entering the system embodied in biobased materials was assumed to correspond to an equivalent amount of carbon sequestered from the atmosphere. Each unit was accounted for as a biogenic carbon dioxide emission when the biobased material exits the system after its end-of-life, regardless of the disposal scenario.

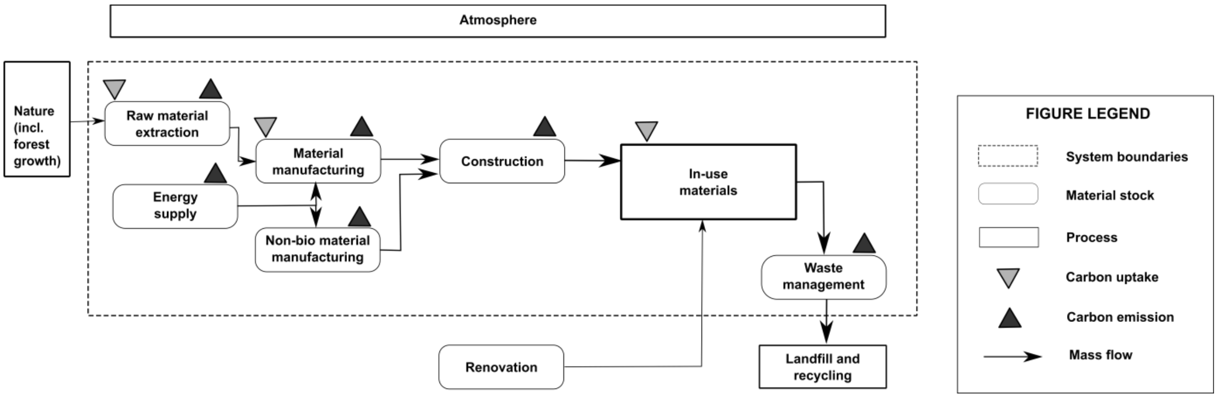

Figure 5 *Boundaries of the systems considered in Paper V, which included processes (manufacturing, electricity generation, construction, and waste management), material stocks, and GHG emissions and sequestration.*

3.3 Accounting for non-traditional aspects in LCA

To address RQ1 and obtain a robust answer for RQ2, it was necessary to establish a methodology for climate impact assessment of the studied cases that addressed as many non-traditional aspects as possible of those outlined in Figure 3. The chosen methodology involved adding data for forest carbon flows in the inventory analysis and applying dynamic LCA for the impact assessment. Expanding the boundaries of the assessed systems to include the forest and its biogenic carbon exchanges with the atmosphere addresses the climate neutrality assumption of biogenic carbon (aspect C in Figure 3). However, this is a complex task since diverse factors affect carbon fluxes and stores in forests, and thus will affect results of a climate impact study, as discussed in section 2.3. These factors (which include the spatial scale used to assess the net carbon balance, the baseline land use in the forest, and the timing of the forest growth before or after harvesting) were considered in more detail through scenario analysis, as described in the next section.

The forest carbon balance at stand level was accounted for using data from the 80-year stand growth model presented by Kilpeläinen *et al.* (2011). Landscape-level balances were acquired by assuming that the forest carbon pools were in equilibrium, so nearly all of the biogenic carbon sequestered in the biobased materials was released from the forest in a single pulse emission in the year of harvesting. To obtain forest carbon data with a natural regeneration baseline, it was assumed that a harvested coniferous forest takes up 20% less carbon dioxide than natural forests, based on above-ground biomass storage factors for natural forests and coniferous boreal forest plantations provided by the IPCC (2006). The carbon pool in the soil was assumed to remain unchanged. The growth timing factor was handled simply by moving the occurrence of forest carbon sequestration in time.

Application of dynamic LCA for impact assessment allowed analysis of three key aspects shown in Figure 3: A (timing of emissions), B (time horizon) and D (effect of carbon storage).

Dynamic LCA was chosen rather than other available methods for two reasons. First, dynamic LCA is a flexible method that allows any type of inventory data to be introduced easily (more conveniently than other methods that may permit this), thereby facilitating accounting of forest carbon flows. Second and most importantly, unlike all other methods dynamic LCA allows accounting for the timing of sequestration and emissions that are not related to the forest, but occur in the future. This is particularly relevant for buildings as they are long-lived products and several of their inventory flows occur in the future. An important example of such flows is the sequestration of carbon dioxide by concrete, a long-term process of demonstrated relevance (Collins, 2010; Wu *et al.*, 2014) known as carbonation. This was one of the main phenomena considered in the study reported in Paper IV, so the chosen method had to allow accounting for the timing of non-biogenic emissions as well as biogenic emissions.

It should be noted that some of the aspects shown in Figure 3 have not been deeply addressed either in Papers I-V or the thesis. Most of them were considered in Paper I using superficial estimations based on previous studies that had demonstrated their influence. Challenges and uncertainties that hindered further analysis of some aspects were also noted in Paper I. For instance, accounting for soil disturbances (Aspect F) was difficult due to a lack of data, as soil carbon disturbances are location-specific so location-specific data are required. Other aspects, such as indirect land use change (aspect G), the albedo effect (aspect H) and aerosols (aspect I) have still received little attention, so both robust methods for handling them and pertinent data are also lacking. Finally, aspect E, related to partitioning flows and impacts among multiple functional processes, is highly relevant and widely studied, but challenging for many types of products, not just biobased products. Thus, it is beyond the scope of this thesis, and was not further considered.

3.4 Scenario analysis for construction works

Effects of several methodological choices related to aspects shown in Figure 3 on the outcome of LCAs of the selected case systems were explored by scenario analysis. This work started in Paper I, where the potential influence of all aspects was tested superficially, using assumptions and factors drawn from previous studies, simplified methods or approaches described in standards and other literature. Worst and best case scenario results were then hand-picked from all possible methodological combinations to illustrate the importance of non-traditional aspects, as well as the frequently substantial ranges of possible outcomes of climate impact assessments of forest products. The subsequent work consisted of focusing on selected aspects and parameters that are important when accounting for them, especially those related to biogenic carbon and timing of carbon emissions and sequestration (A, B, C, D; Figure 3 and Table 3). The way these parameters were tested using scenario analysis in the appended papers is summarized in Table 3, which briefly describes the basic and alternative settings for each scenario studied.

Table 3 *Summary of the methodological settings tested in II, Paper III and Paper IV using scenario analysis.*

Studied parameter	Related aspect (Fig 3)	Paper and case study	Basic setting	Alternative setting(s)
Timing of forest growth (before and after harvest)	A, C, D	Papers II and III (building)	Regrowth (after)	Growth (before)
		Paper IV (bridge)	Regrowth (after)	Growth (before) 50/50 (half growth before, half after)
Time horizon of impact assessment	B	Papers II, III and IV (both)	All from 0 to 300 years were calculated	
Service life of construction work	D	Paper II (Building)	50 years	70 years
Biobased content of construction work	D	Paper II (Building)	~ 50%	0 % ~ 69%
End-of-life scenario (biobased materials)	D	Paper II (Building)	90% incineration, 10% recycling	70% landfill, 10% incineration
End-of-life scenario (benchmark)	A	Paper IV (Bridge)	Recycling	Crush and expose
Spatial perspective for forest carbon sequestration	A, C	Paper III (Building)	Stand approach	Landscape approach (equilibrium) National (increased forest carbon)
		Paper IV (Bridge)	Stand approach	Landscape (equilibrium)
Land use baseline at forest	C	Paper III (Building)	Zero baseline	Natural regeneration
Biogenic carbon flows	C, D	Paper IV (Bridge)	Biogenic carbon flows included in LCI	Biogenic carbon flows excluded in LCI
Timing of emissions (benchmark)	A	Paper IV (Bridge)	Concrete carbonation sequestration included in LCI	Concrete carbonation sequestration excluded in LCI

3.5 Scenario analysis for the building stock

A scenario analysis was also applied in Paper V, in which future scenarios were constructed to represent various technological trends that are influencing and/or may influence the Swedish building stock. They mostly concerned the rise in use of biobased materials in buildings, the evolution of the Swedish energy mix, proportions of single- and multi-family dwellings, and the rapid increase in low-impact concrete building construction. This enabled evaluation of benefits of increasing the use of biobased materials in the Swedish building stock under various future settings. A “business as usual” scenario representing the continuation of past trends obtained from statistics was used as a baseline, and seven alternative scenarios with different combinations of the mentioned variables were constructed, featuring optimistic and pessimistic temporal developments. These scenarios are summarized in Table 4.

Table 4 *Description of the eight future scenarios considered in Paper V. 'Four futures' refers to the 'Fyra framtider' project (in Swedish, Swedish Energy Agency, 2016).*

Variable	Baseline scenario	Bio moderate - Energy optimistic scenario	Bio moderate - Energy pessimistic scenario	Bio optimistic - Energy optimistic scenario	Bio optimistic - Energy pessimistic scenario	Climate optimistic scenario	Climate pessimistic scenario	Climate strictest scenario
Growth rate of share of total new HFA built using timber building systems	Business as usual; share continues to grow yearly by 0.2% until share of normal concrete reaches 0%	Share grows yearly by 1% until share of normal concrete reaches 0%	Share grows yearly by 1% until share of normal concrete reaches 0%	Share grows yearly by 2% until share of normal concrete reaches 0%	Share grows yearly by 2% until share of normal concrete reaches 0%	Share grows yearly by 1% until share of normal concrete reaches 0%	Share grows yearly by 0.1%	Share grows yearly by 2% until share of normal concrete reaches 0%
Change in energy supply	'Espressivo' scenario from 'Four futures'	'Vivace' scenario from 'Four futures'	'Forte' scenario from 'Four futures'	'Vivace' scenario from 'Four futures'	'Forte' scenario from 'Four futures'	'Vivace' scenario from 'Four futures'	'Forte' scenario from 'Four futures'	'Legato' scenario from 'Four futures'
Growth rate of share of total new HFA built using low-impact concrete building systems	Assumption; conventional high-impact concrete is phased out by 2040	Same as Baseline	Same as Baseline	Same as Baseline	Same as Baseline	Conventional high-impact concrete is phased out by 2035	Conventional high-impact concrete is phased out by 2050	Conventional high-impact concrete is phased out by 2030
Distribution of new HFA built per typology; share of 1-2 family and multifamily dwellings	Business as usual; the share of multi-family dwellings keeps growing yearly by 0.4%	Same as Baseline	Same as Baseline	Same as Baseline	Same as Baseline	The share of multi-family dwellings grows yearly by 1% until share of 1-2 family dwellings reaches 20%	The share of multi-family dwellings decreases yearly by 0.4% until it reaches 40%	The share of multi-family dwellings grows yearly by 1% until share of 1-2 family dwellings reaches 20%

4 Results and discussion

Results of the studies presented in the appended papers are discussed in this section, in relation to each of the research questions expressed in section 1.3. Each subsection deals with one of the research questions, and addresses specific issues (see bullet points below) that are relevant for the overall themes of the thesis.

4.1 Aspects of climate impact assessment of biobased materials

This subsection considers results presented in the appended papers in relation to RQ1: *What important aspects are missing from the common practices in climate impact assessment in LCA of biobased building materials and how much can they affect the outcome?*

- Defining the 'common practices' in climate impact assessment of biobased products

The outcome of the literature review reported in Paper I can be considered a representation of the common practices in climate impact assessment of biobased products, according to scientific publications, with respect to the key aspects identified in Figure 3 and how they are addressed. When analyzing biobased products, LCA practitioners commonly do not consider timing of emissions or storage effects, assume climate neutrality of biogenic carbon, use a fixed time horizon of 100 years and exclude phenomena such as changes in soil organic carbon, albedo effect and indirect land use effects. Furthermore, many studies do not clearly state how some of these aspects are handled, which is a concern as their inclusion can substantially affect the results.

- How much can including non-traditional aspects affect results for a building?

Including these aspects in an LCA of biobased products is highly important, as demonstrated by results of the building case study presented in Paper I. The differences between the highest and lowest possible impacts and those obtained following common practices can be seen in Figure 6. The results show that changes in practices used to handle the non-traditional aspects could almost double the net life cycle climate impact of the building, in CO_2 emission equivalents, relative to the impact associated with the common practices, or even turn negative. More importantly, the introduction of non-traditional aspects could also significantly affect the comparison with a concrete building. It should be noted that the introduction of non-traditional aspects also affected the concrete alternative because of the use of bioenergy in all life cycle stages and the presence of some biobased materials in certain elements of the concrete building. The effects were still substantial; the difference between both alternatives exceeded almost by a factor of four with the lowest possible result setting if compared to the common practices, while with the highest possible result setting the impact of the CLT building even surpassed that of the concrete building. The influence of non-traditional aspects in this case study were somewhat reduced by the dominance of the operational energy in the life cycle impact of the building. However, in a case study where bioenergy is predominantly used during operation or where operational energy use is greatly reduced, the influence would be stronger.

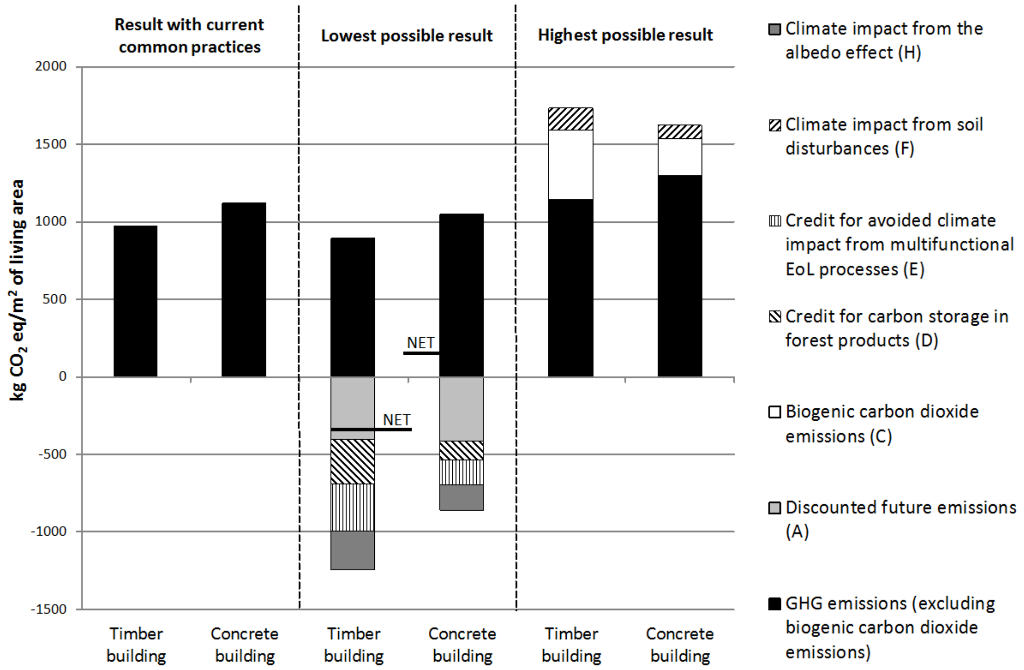

Figure 6 *LCA results for the building systems considered in Paper I, illustrating potential effects of introducing non-traditional aspects on life cycle climate impacts of a CLT building in comparison to an equivalent concrete-based alternative. The figure compares the net climate impact obtained without considering non-traditional aspects (common practices) to those obtained with methodological settings that do account for non-traditional aspects. Results of possible assumption settings that yielded the highest and lowest impacts are shown in the figure. The contribution of the non-traditional aspects studied (see Figure 3) is specified in each series.*

- The importance of the forest system for non-traditional aspects

Biogenic carbon flows and the way they are accounted for in the life cycle inventory are key elements of the non-traditional aspects addressed in this thesis: the timing of emissions, time horizons of climate metrics, climate neutrality and credits for carbon storage. There are two main types of biogenic carbon flows in biobased material systems; the carbon sequestration from the atmosphere that occurs during forest growth and the emissions to the atmosphere that occur at end-of-life. The way biogenic carbon sequestration in the forest is inventoried depends on several assumptions and methodological choices that were considered in all the appended papers.

One of these choices is the timing of forest growth. Dynamic LCA is an approach to quantifying climate impacts that acknowledges the importance of the timing of each GHG flow. That is why accounting for biogenic carbon sequestration before or after harvesting can affect the contribution of biogenic carbon flows to the overall result, and the magnitude of credits for carbon storage in products. For example, in the building case study presented in Paper III (Figure 7) placing forest growth after harvesting (Setup 1) yielded different results from placing it before harvesting (Setup 2), and the difference was significantly greater for short time horizons. It is not easy to establish a correct approach in this respect, since it can be argued that forest regrowth is a consequence of harvesting or that the biomass stored in the building started to sequester carbon dioxide long before it was harvested. However, a '50/50' approach was proposed in Paper IV as a practical compromise, in which half of the growth is accounted for before harvesting and the other half is accounted for after harvesting.

The spatial framework of analyses of biogenic carbon sequestration and its changes over time is another important element, which was addressed in Paper III. In a single boreal forest stand, the biogenic carbon is sequestered in biomass gradually over a 'standard' rotation period of 80 years (in the absence of catastrophic events such as major storms). However, at landscape, regional or larger scales sequestration rates must be based on the net carbon balance of the landscape (or larger geographical area). This balance depends on harvesting practices, and may be positive or negative depending on the difference between amounts of carbon sequestered by trees and amounts leaving the forest in the form of emissions or biomass each year.

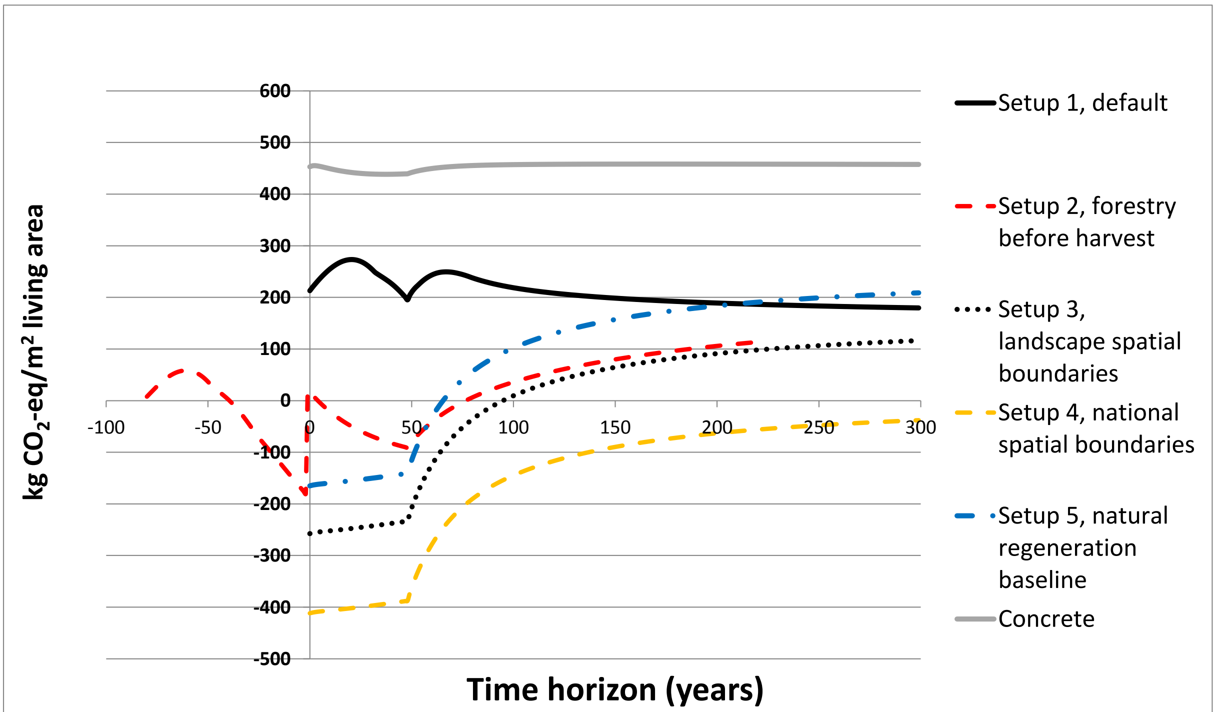

Figure 7 *Cumulative climate impact relative to the impact of 1 kg* CO_2 *emission at year zero (*GWI_{rel}*) calculated by dynamic LCA for the CLT building and benchmark of the case study presented in Paper III. The curves show results obtained with different methodological setups for accounting for forest carbon sequestration, with respect to spatial boundaries, temporal boundaries and land use baseline.*

As shown in Figure 7, the default approach in Paper III included a stand perspective, which was contrasted with approaches including a landscape (Setup 3) or national (Setup 4) perspective. The stand approach implies a net carbon balance of zero, given that the amount of biogenic carbon sequestered is equivalent to that stored in the product, and therefore emitted at end-of-life. The deviation from a zero in net carbon balance obtained with this setup is due to the timing of the growth, as growth rates in dynamic LCA depend on the type of forest, species present and timing of flows. On the other hand, the net carbon balance of a forest at landscape and national levels can vary depending on the scale of the measurements. At landscape (or larger) scale there is usually a net growth in carbon stocks in Swedish forests, thus the carbon sequestered exceeds the carbon stored in products and emitted at end-of-life, which reduces the climate impact of the CLT building. As for the timing of growth assumption, the results were significantly more sensitive to the choice of spatial perspective when a short time horizon was used for impact assessment.

The net carbon balance in the forest can also vary depending on the land use baseline assumed for the assessment. The discussion in the previous paragraph applies only if a "zero baseline" is assumed, so there is no counterfactual situation and the inventory flows are simply measured as total amounts. However, if a 'natural regeneration' baseline is applied, as in Setup 5 of Paper III (Figure 7), the net carbon balance is measured in comparison with a counter-factual situation where the forest is left to naturally regenerate after one harvest. Since natural forests sequester biogenic carbon faster than harvested forests, the resulting net carbon balance was negative and the biogenic carbon emitted at end-of-life offset the carbon sequestered, increasing the climate impact of the CLT building. As for the previous assumptions, the results were more sensitive to this choice if a short-term time horizon was used.

4.2 Increased use of biobased materials in construction works

The discussion in this subsection focuses on the findings of Papers I-V that help efforts to address RQ2: *What are the climate impacts or benefits of increasing the biobased material content in construction works?*

- Case-specific factors are highly relevant for non-traditional aspects

The discussion in the previous sub-section showed that assumptions related to biogenic carbon sequestration in the forest can substantially influence non-traditional aspects of climate impacts that should be considered. Similarly, there are assumptions that affect biogenic carbon emissions at the other end of the life cycle of biobased building materials. These assumptions are not related to the forest but to the life cycle of the building, as the timing of end-of-life biogenic carbon emissions, or duration of carbon storage periods, are highly relevant in dynamic LCA.

One of these assumptions concerns the service life of the construction, which was explored in Paper II, where results obtained with service lives of 50 years and 70 years were compared. Prolonging the service life increased the percentage reduction in climate impact of both the CLT building and increased bio alternatives with respect to the concrete building, as shown in Table 5. The results from Paper III also suggest that extending service lives enhances climate impact reductions, as the benefits of replacing non-biobased products with biobased alternatives were larger for long-lived than for short-lived products. However, the increased need for maintenance should be taken into account if the assumed service life of a building is extended. Biobased products usually have shorter service lives than non-biobased alternatives, and thus must be replaced more frequently. Maintenance assumptions were not deeply addressed in the appended papers apart from a sensitivity analysis in Paper IV, where a worst-case maintenance scenario for the timber bridge was analyzed. Even in this worst-case scenario, the timber bridge had the lowest climate impact. Therefore, extending the service life of a biobased building has clear potential as a climate mitigation strategy, but it should be treated with caution. Finally, it is worth noting that, like most assumptions discussed so far, the climate impact reductions achieved by extending the service life were less pronounced with a long-term time horizon.

Table 5 *Summary of the cradle-to-grave climate impact assessment results obtained for the three building designs evaluated in Paper II. The % reduction indicates the difference between the concrete design and the CLT-based and increased bio designs.*

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

The climate benefits of increasing the service life arise from the longer storage of biogenic carbon. In addition to extending the service life, with caution, another way to extend the storage period of biogenic carbon is to recycle the biomass at end-of-life. The climate benefits of extending the storage period of biogenic carbon through recycling were demonstrated by scenarios presented Paper II. More specifically, 70% end-of-life landfilling of the biobased materials in the buildings resulted in significantly less impacts than predominantly disposing of them by incineration (see Table 5). However, the 70% landfilling assumption was quite unrealistic since landfilling biobased products is not allowed in Sweden and other European countries.

A more realistic scenario would be to recycle the biomass so the biogenic carbon remains stored in the technosphere beyond the end-of-life of the building. However, this would present accounting challenges as the impacts of biogenic carbon flows, and thus the positive effects of carbon storage, would need to be distributed among the multiple products or functions provided by a given amount of biomass. The challenging part is that under current standards in an LCA context the biogenic carbon stored in the product should be treated similarly to other embodied characteristics; even if recycled they should be treated as emissions when leaving the studied system and as an uptake in the product system that uses the secondary material. Thus, an approach to deal with recycling and biogenic carbon storage benefits is still needed, which represents reality better than the approach applied in the study reported in Paper II. This issue also emerged in Paper IV, which showed that re-using the concrete from the concrete bridge in road construction after end-of-life provided subsequent climate benefits from the continuation of concrete carbonation. The additional benefits in this scenario needed to be allocated among the two products that contained the same concrete: the bridge and later the road. This issue needs to be addressed in order to apply LCA in circular models and material cascading approaches, which are becoming increasingly widely applied.

- The optimal climate approaches for assessing climate impacts of construction works and other types of products differ.

The results presented in Papers II, III and IV highlight the importance of the choice of time horizon, as the impact results of the case studies varied considerably over time. This choice is arguably most important for construction works since they are long-lived products and their service life is rarely less than 50 years. The radiative forcing caused by any pulse emission of carbon dioxide rises and accumulates for a period of 100 years, and then somewhat stabilizes. Therefore, when using an approach for assessing climate impacts such as dynamic LCA that consider the timing of pulse emissions as well as their amounts, any time horizon shorter than 100 years will exclude parts of the impacts from the results. This is particularly problematic for analyses of long-lived construction works since important fractions of the impacts occur in the future, at (or beyond) the end-of-life. It is also highly problematic for forest products, as significant shares of stand-level impacts will occur after the end of 80-year rotation periods, and be excluded. This explains why application of short and long time horizons considerably affected results for all the scenarios addressed in the appended papers. Moreover, since short time horizons result in excluding a sizable share of impacts, longer time horizons should generally be preferred for the sake of completeness. In short, for analyses of materials like long-lived forest products, where GHG flows in the inventory span long periods of time, the time horizons for climate impact assessments should be accordingly long.

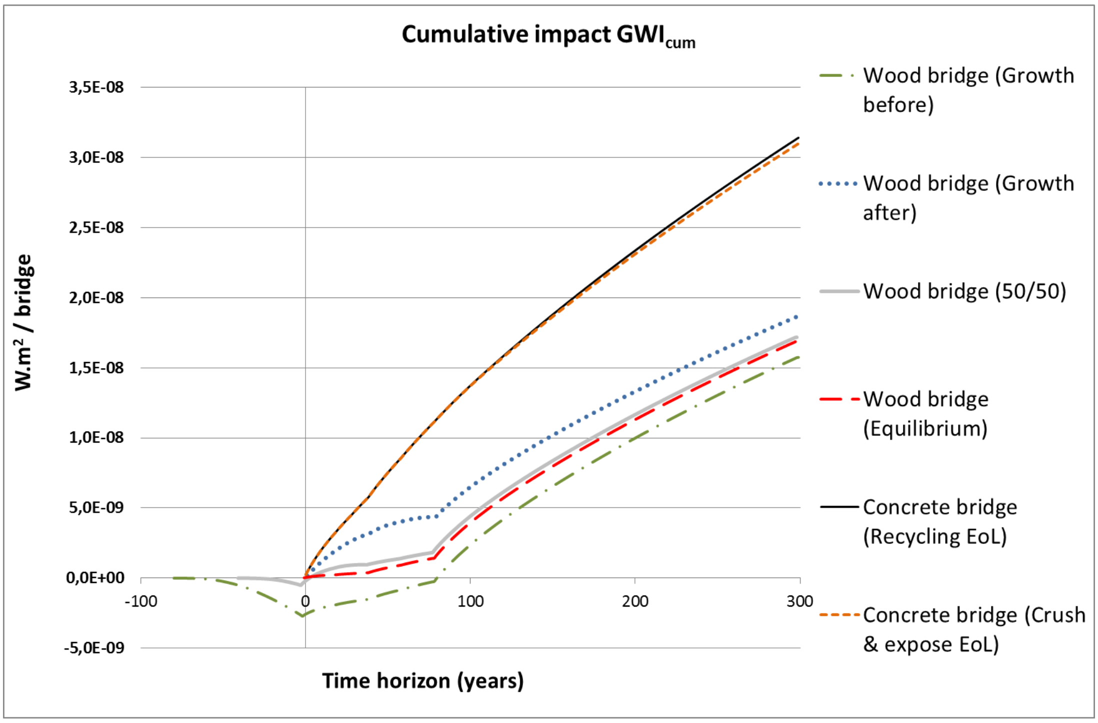

Figure 8 *Cumulative climate impact results for the bridge designs considered in Paper IV. Each function in the figure corresponds to one of the approaches explored for both designs related to two key assumptions; accounting for biogenic carbon sequestration (wood bridge) and the end-of-life scenario (concrete bridge).*

In section 2.4 it was noted that several approaches can be used to assess the climate benefits of biogenic carbon storage in products, but dynamic LCA was chosen, partly because it allows accounting of non-biogenic future emissions. This argument is supported by the results from Paper IV, where dynamic LCA was successfully applied to study a concrete bridge where future GHG emissions were part of the inventory. It can be argued that this was also the case for some of the other appended papers. Still, in Paper IV the phenomenon of concrete carbonation was also studied, which is not commonly accounted for in LCA of construction works.

Concrete carbonation can be regarded as the re-absorption of carbon emitted during the manufacture of concrete via calcination of surfaces exposed to air. It also occurs gradually throughout the service life and even after end-of-life of concrete structures if the concrete is exposed to air. Thus, in stark contrast to biogenic carbon storage, carbon is first emitted (as carbon dioxide) and later partially re-absorbed in the concrete life cycle. This is manifested in the relatively low magnitude of the difference made by accounting for concrete carbonation, as shown in Figure 8. Nevertheless, accounting for concrete carbonation could significantly influence an LCA result depending on the assumptions made, as demonstrated by other studies (see section 3.3). Since significant fractions of carbon dioxide flows occur in the long-term, the approach used to assess climate impacts must allow the capture of concrete carbonation as well as biogenic carbon storage. Moreover, as previously mentioned, concrete carbonation is not the only non-biogenic flow that occurs in the distant future in life cycle systems of construction works. In LCA practice the benchmark products and their characteristics must also be considered when making methodological choices, which supports the choice of dynamic LCA for the work presented in this thesis.

- Increasing biobased material contents in designs reduced climate impacts in every studied scenario

Finally, for this subsection, it should be noted that the alternatives with biobased material contents always had lower climate impacts than the concrete benchmarks in all of the scenarios evaluated in Papers II, III and IV. The gap between biobased and concrete designs for the evaluated construction works varied significantly, depending on the time horizon chosen and/or settings for all the assumptions discussed so far in this section. Nevertheless, increasing the amount of biobased building materials consistently abated calculated climate impacts. However, due to this variation in gaps, decision-makers should use LCA results cautiously when evaluating effects of different climate mitigation strategies involving biobased materials. Different scenarios should be evaluated to avoid overestimating the magnitude of climate benefits. In addition, practitioners should bear in mind this uncertainty and the results presented in Paper I (the substantial difference between highest and lowest possible results) when assessing climate impacts of construction works with high contents of biobased materials, when either choosing methodology or communicating results.

4.3 Increased use of biobased materials in the building stock

This subsection addresses the third and final research question (RQ3), summarizing the findings from Paper V: *What are the climate impacts or benefits of increasing the use of biobased materials in the Swedish building stock in the long-term future?*

- Increasing the use of biobased materials in new building construction decreases the cumulative climate impact, mainly when introducing biogenic carbon and under certain metrics.

The long-term climate impact of the Swedish building stock in eight scenarios with varying uses of biomaterials in the construction of new buildings was evaluated in Paper V. Several conclusions can be drawn from the results (summarized in Figure 9), but most importantly mitigation of climate impacts was strongest in scenarios with a rapid increase in use of biobased materials. However, the difference made by the increased use of biobased materials was substantially less noticeable when GWP100 was used as a metric. This can be explained by the fact that in the long-term future and under the assumptions made in the model used in Paper V, the gap in climate impacts of timber and concrete buildings will be greatly reduced by the changes in the energy system and the manufacturing of cement. Therefore, the outcome will be similar as long as high-impact concrete is phased out rapidly.

This outcome changed to a large extent with the introduction of biogenic carbon flows and concrete carbonation to the model and the use of alternative metrics. When other metrics than GWP100 were used, the gap between the different scenarios expanded significantly. This shows that introducing non-traditional aspects in a study with a broader scope can also make a difference to the results. Results were also sensitive to the choice of metric to calculate climate impacts, more specifically a metric that captures biogenic carbon storage and timing of emissions.

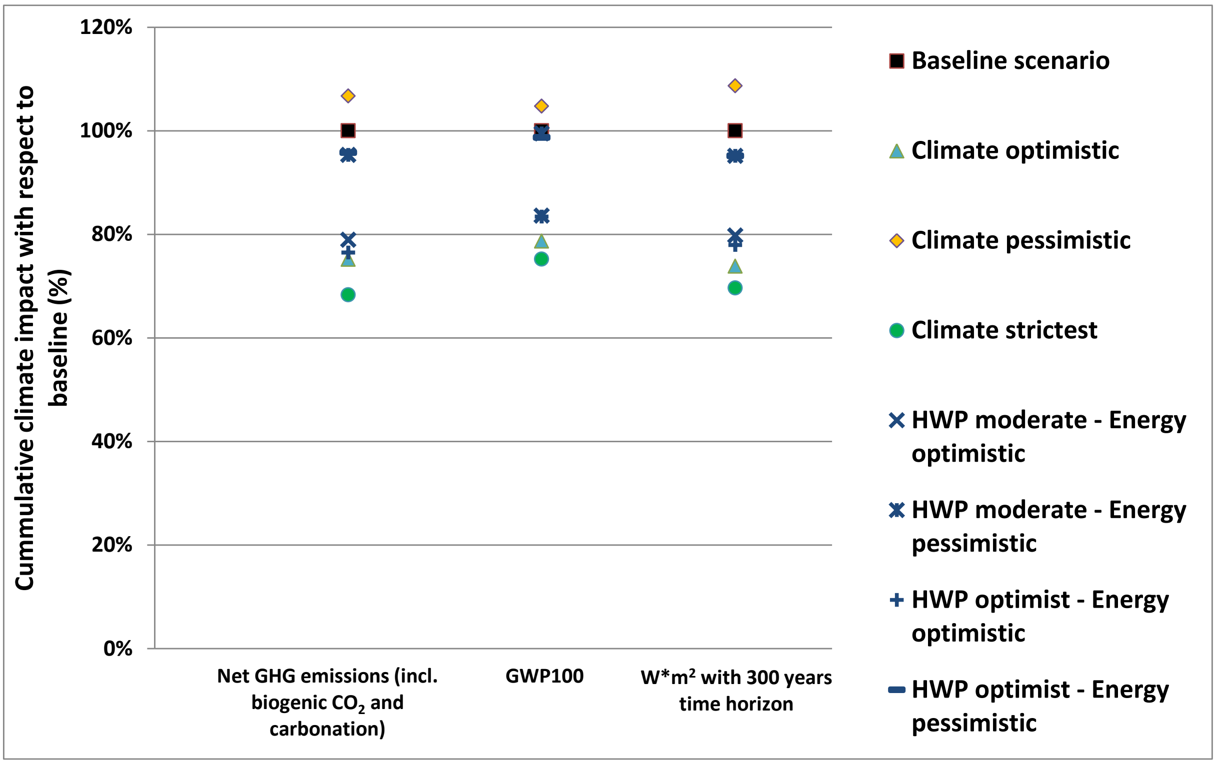

Figure 9 *Comparison of results of the cumulative impact assessments, relative to the baseline, under each of the considered scenarios.*

- Assumptions about technological change substantially influence climate impact assessments

The results shown in Figure 9 also demonstrate the magnitude of the influence of accounting for changes in technology on the outcome of long-term assessments of climate impact at the building stock level. The results varied significantly depending on the assumptions made regarding long-term changes in the energy production system. This can be seen in the differences between the two 'Energy optimistic' and 'Energy pessimistic' scenarios, which were evaluated under different assumptions for developments in the energy sector. These assumptions strongly influence temporal dynamics of the impact of building materials' manufacture over time, and thus the expected climate impact per unit of material produced and used in the future. The significance of these assumptions highlights the importance of accounting for technological changes in long-term modelling of climate impacts of buildings. This significance can also be observed equally in all the climate impact metrics applied.

- Climate impact mitigation results are maximal when increased use of biobased materials is combined with other strategies

Of all the scenarios analyzed in Paper V, the 'climate strictest' scenario resulted in the lowest cumulative climate impact (Figure 9). This scenario combined the most optimistic increase in use of biobased materials in buildings with optimistic assumptions for all the studied variables. This indicates that increasing use of biobased material is not the only effective option for mitigating the climate impact of building construction, and other strategies can be implemented simultaneously and synergistically. The goal of the construction sector should not be to replace concrete buildings, but rather to phase out high-impact concrete buildings and substitute them with alternative systems. As demonstrated by results presented in Paper V, some alternatives can be found in the concrete industry as well, and the best results were obtained in scenarios where increased use of biobased materials was implemented simultaneously with other mitigation strategies.

5 Conclusions and future work

The aim of the research work presented in this thesis was to create knowledge for enhancing understanding of the climate effects of increasing use of biobased products in the Swedish construction sector. The strategy to address this aim was to identify aspects of climate impact assessment of biobased materials that may be influential but are seldom accounted for by practitioners. Then, these aspects were explored in a variety of case studies, through scenario analysis, testing the effects of various methodological settings and assumptions in the climate impact results. This section summarizes the learning outcomes from the discussion in section 4, starting with the findings related to the climate mitigation potential of increasing the use of biobased products in buildings, followed by findings regarding the methodology for climate impact assessment of construction products with high biobased material content. Finally, possible ways to extend findings presented in this thesis are discussed.

5.1 Towards a biobased construction sector

- Increasing the use of biobased materials can mitigate climate impacts of construction.

In the vast majority of scenarios, with nearly all methodological settings used to assess the climate impacts of construction works, lower impacts were obtained for alternatives with higher contents of biobased materials. The choice of methodology always influenced the results to a certain extent, but although the selected assumptions and time horizons affected the gaps between alternatives, they seldom altered rankings of alternatives. Similarly, in building stock assessments, the obtained long-term climate impact reductions were consistently stronger in scenarios with faster growth in use of biobased materials in the building stock, regardless of how other methodological settings and assumptions were handled.

- Additional strategies concerning building materials are needed to maximise the climate mitigation potential.

There are also other strategies involving choices of materials to mitigate the climate impacts of buildings besides increasing the use of biobased materials. Rapid implementation of these strategies in Sweden would reduce the relative long-term impact reductions obtained from increasing amounts of buildings with high contents of biobased products. This is especially true for energy-intensive alternatives, given the substantial efforts to reduce the climate impacts of energy supply. However, long-term climate mitigation will be maximised if all effective strategies are implemented simultaneously. Due to the urgency of the climate change problem, all these strategies should be rapidly implemented in order to replace current conventional high-impact concrete-based building systems with lower-impact options.

5.2 Climate impact assessment of biobased materials

- The assumption of biobased building materials' climate neutrality is an oversimplification and biogenic carbon flows should be accounted for.

Biobased building materials are widely assumed to be 'climate neutral', i.e. to have no net effects on CO_2 emissions. However, biogenic carbon flows that can be attributed to forest biomass harvesting are not usually neutral, so they should be accounted for in climate impact assessments of buildings with high contents of biobased materials. The validity of the climate neutrality assumption heavily depends on the carbon balance in the forest, which is influenced by case-specific factors. These factors include the timing of the occurrence of forest carbon sequestration, the spatial perspective applied in measurements of these flows, the baseline land use in the forest, the end-of-life scenario for biobased materials and the storage periods of biogenic carbon in products. As these factors are case-sensitive, it should not be simply assumed that biobased building materials are always climate neutral.

- Climate metrics that allow accounting for timing of biogenic and non-biogenic carbon emissions and the use of long-term time horizons should be prioritized in order to fully capture the climate impacts of construction works.

Results of all studied scenarios were substantially affected by the selected time horizon, which is therefore one of the most important parameters in climate impact assessments of buildings with high biobased material contents. This is not surprising, as construction works are long-lived products, so significant shares of associated emissions occur in the future, including non-biogenic flows associated with processes such as concrete carbonation. It is important not only to account for the timing of all emissions, but also to measure climate impacts with long-term time horizons to capture the full effect of all the relevant flows. This is particularly important for products made from biomass harvested in boreal forests, since they have long rotations, and it takes a long time for carbon sequestration during forest growth to have a significant cumulative climate impact. Therefore, GWP100 is a metric that does not capture all the environmental effects in climate impact assessment of construction works with high contents of biobased materials. On the other hand, dynamic LCA is a suitable approach since biogenic and non-biogenic emissions can be assessed according to their timing with any time horizon. Dynamic LCA also allows accounting for the positive effect of temporary biogenic carbon storage, which is not yet generally accepted in current LCA practice.

- Practitioners must clearly state how relevant non-traditional aspects are handled in their LCAs, and different scenarios should be explored.

Results presented in this thesis show that various aspects that are not traditionally included in climate impact assessments of biobased products have substantial effects on the results. Many studies give no reason for excluding these aspects, but the methodology and assumptions used to deal with them should be clearly stated in every study for the sake of transparency, completeness and reproducibility. Moreover, to reduce uncertainty, evaluation of multiple scenarios with alternative methodological settings (including variations in the handling of non-traditional aspects) is recommended.

5.3 Future work

The 'bioeconomy' concept is receiving increasing attention in Sweden due to the vast forest resources available, and there is a global trend towards development of a 'circular economy', i.e. making material flows in the anthroposphere circular and (hence) the concept of waste obsolete. In combination, these trends lead towards circular biomass flows, which require analysis by cascade models rather than static end-of-life accounting of biomass and energy production. Thus, LCA must be adapted to these product systems, including the non-traditional aspects addressed in this thesis, most of which affect the impact of a given amount of biomass that is going to be shared by various cascading products. Therefore, biogenic carbon and its related aspects must be allocated among various products for appropriate numbers of consecutive life cycles, and LCA must be adapted accordingly.

The trend toward development of a bioeconomy is expected to stimulate increases in the use of wood in construction. Increases in value of centrally located construction projects have stimulated increased interest in high-rise timber buildings. Construction of such buildings would introduce requirements for additional measures to overcome expected challenges related to issues such as fire safety, noise, vibration and stability. These additional measures imply additional climate impacts, which could directly affect roles and effects of biobased materials in the building sector and its climate mitigation strategies at both single structure and sectoral levels. Similarly, changes in maintenance requirements associated with extending the service life of timber buildings could affect aspects considered in this thesis, and should be examined more thoroughly in future studies.

The study of climate impact mitigation at the sectoral level presented in this thesis demonstrated the importance of technological changes. The model used to forecast long-term climate impacts could be improved by using alternative approaches to estimate material or emission flows, approaches such as input-output data or supply-demand theoretical frameworks. It could also be extended to include infrastructure, maintenance, and other structural typologies of interest such as high-rise timber buildings.

Finally, the non-traditional aspects shown in Figure 3 that were not considered in this thesis require attention when more robust methods are available to do so. Changes in soil organic carbon pools, land use changes, albedo effects and aerosol emissions could all affect roles of biobased materials in the climate mitigation of construction. Moreover, other impact categories that are beyond the scope of this thesis could be affected by increasing forest harvests, and therefore should be studied. These include aspects such as impacts on biodiversity, water use and biotic resource depletion, which also need to be addressed before mitigation strategies based on increased use of biobased materials are implemented.

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CONTRIBUTION TO APPENDED PAPERS

The authors' contributions to the work reported in the appended papers were as follows:

I. Røyne, F., Peñaloza, D., Sandin, G., Svanström, M., and Berlin, J. (2016). Climate impact assessment in LCAs of forest products: Implications of method choice for results and decision-making. *Journal of Cleaner Production* 116, pp 90-99.

Peñaloza, Røyne and Sandin carried out the literature survey and wrote the article. Peñaloza provided the results for the building case study. Røyne coordinated the work and provided the results for the fuel case study. Sandin wrote most of the method and discussion in section 5. Svanström and Berlin provided guidance and expert feedback.

II. Peñaloza, D., Erlandsson, M., and Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. *Construction and Building Materials* 125 (2016), pp 219-226.

Peñaloza carried out all the modelling, calculations and writing of the article. Erlandsson and Falk provided guidance and expert feedback.

III. Peñaloza, D., Røyne, F., Sandin, G., Svanström, M., and Erlandsson, M. The influence of system boundaries and baseline in climate impact assessment of forest products. Submitted to the *International Journal of Life Cycle Assessment* (March 2016).

Peñaloza provided the results for the building case study, performed all the dynamic LCA calculations and wrote the results, discussion and conclusion sections of the article. Røyne provided the results for the chemical and automotive fuel case studies and wrote most of the method section. Sandin provided the results for the textile fibers case study and wrote most of the introduction section. Svanström and Erlandsson provided expert feedback.

IV. Peñaloza, D., Erlandsson, M. and Pousette, A. (2017). Climate impacts from road bridges: Effects of introducing concrete carbonation and biogenic carbon storage in wood. *Structure and Infrastructure engineering*. DOI: 10.1080/15732479.2017.1327545.

Peñaloza carried out all the modelling, calculations and writing of the article. Pousette provided expert feedback and inventory data for the wooden bridge. Erlandsson provided expert feedback.

V. Peñaloza, D., Erlandsson, M., Berlin, J., Wålinder, M., and Falk, A. Future scenarios for climate change mitigation of new building construction in Sweden: Effects of different technological pathways. Manuscript submitted to *Building Research and Information* (May 2017)

Peñaloza carried out all the modelling, calculations and writing of the article. Erlandsson, Wålinder, Berlin and Falk provided guidance and expert feedback.