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Climate impacts of carbon sequestration of forests and material substitution by energy biomass and harvested wood products under boreal conditions

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Academic dissertation

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ABSTRACT

This study aimed to investigate the climate impacts of carbon sequestration in forests, and the substitution of fossil energy (e.g., coal, oil) and fossil-based materials (e.g., concrete, steel, plastic) with harvested energy biomass and timber (pulpwood, sawlogs) under Finnish boreal conditions. The study employed forest ecosystem model simulations and a life cycle assessment tool to calculate the net CO_2 exchange for the forest-based biosystem. The effects of stocking in thinning, nitrogen fertilization, and the use of varying rotation lengths (Papers I–III) and harvest intensities in final felling (timber, logging residues, with and without coarse roots and stumps) (Papers I, III) on the climate impacts and economic profitability of biomass production (Papers I, III) were studied. Current Finnish forest management recommendations for thinning, aimed at timber production, were used as a baseline. In addition, the sensitivity of climate impacts to displacement factors and timber use efficiency was studied (Paper II). This work was conducted at the stand level, with a mature stand as a starting point (Paper I), at the landscape level, under alternative initial forest age structures (Paper II), and at the regional level, using national forest inventory data in southern Finland (Paper III).

This study revealed that the best option for increasing the climate impacts of biomass production and utilization was through maintaining up to 20% higher stocking, nitrogen fertilization, and using 80–100-year rotations, since they increased carbon sequestration and timber and energy biomass yields (Papers I–III). However, there was a tradeoff between the greatest climate impact and the economic profitability of biomass production (Papers I, III). Sawn wood products were the best option for long-term substitution and increasing carbon stocks of wood products (Papers I–III). It was also found that the effects of substitution and timber use efficiency on climate impacts were higher than those of the thinning regimes (Paper II). Consequently, the greatest climate impacts were found when intensified biomass harvesting was performed, and the prominent regions for increasing climate impacts over the next 40-year period were the southern and eastern sub-regions of Finland (Papers I, III). Furthermore, the climate impacts were found to be sensitive to the initial conditions set for the analyses, which affected the timing of the climate impacts and the preference of forest management in climate change mitigation. This indicates that management measures, together with the initial conditions of the forests, should be considered when evaluating efficient options for increasing climate impacts by forests and substitution.

Keywords: carbon sequestration, carbon stock, climate impact, displacement factor, emissions, fossil-based materials, life cycle assessment, net present value

PREFACE

At this point of no return, I profoundly recall my father (late Surjya Kanta Baul), a noble English teacher and writer, who had some impacts on me. My father kindled my inner impulse for teaching and research, since I used to observe the way he taught and delivered speeches, which was hypnotizing. His inspiration and enthusiasm for higher studies was what animated me to pursue a degree. My father wanted to see me do a degree, and I developed a passionate dream for undertaking a doctorate degree in forestry at a renowned university. My dearest mother (Ashima Baul) keenly wanted me to fulfill my father's desire, and my dream has now come true. I also acquired a lesson from my mother, who has enormous endurance and a calm character, in how to tackle difficulties in moving forward. My parents' unconditional affection and zeal has always made me feel more capable in this journey of finishing my degree.

This moment reminds me of my late grandmother, who had the great virtues of generosity and simplicity, showed me the path for being better human. No words are enough for my parents and two elder brothers (journalists), Sanath Baul and Pranab Baul. From the beginning, my beloved elder brothers, sister (Susmita), brother-in-law (Shomen), sisters-in-law (Shaptarshi & Sumi), charming nephews, nieces, and enthusiastic cousins have always been with me with their everlasting love and mental support, helping me to reach this position. I owe everything to all of them. Many thanks to all my lovely relatives, especially maternal and paternal uncles and aunts, without whose continuous encouragement through these years, this dissertation would not yet have been completed. I love all of them, and I dedicate this thesis to my parents, grandmother, brothers, sister, extended family members, and relatives, who have been eagerly anticipating for.

I would like to express my heartiest gratitude to Dr., Docent Antti Kilpeläinen, Senior Researcher (main supervisor) and Dr. Ashraful Alam for their proficient guidance, valuable advice, and expert comments throughout my doctoral research. This research work was conducted under the internationally renowned research group of the 'Dynamics and Management of Boreal Forests' at the School of Forest Sciences, University of Eastern Finland (UEF), Finland. I would like to thank, wholeheartedly, the head of the research group, Prof. Heli Peltola, who endorsed my joining of this group, and who offered suggestions continuously, from the beginning to the end. I am deeply indebted to Mr. Harri Strandman for his technical assistance during my research work. I am profoundly grateful to Prof. Antti Asikainen, Natural Resources Institute, Joensuu, Finland for his valuable time in being a mentor in this work. My deep appreciation goes to all of my co-authors for their sincere contributions to the research. I am also heartily thankful to the head of the school, and all the administrative staff, for their supportive roles in dealing with the logistics underpinning my research work.

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I cordially thank all the wonderful and philanthropic Finnish people for helping me to settle here. I am obliged to all of my research colleagues and fellows, at and outside, the School of Forest Sciences of the UEF, for being supportive in tangible and intangible ways. Research fellows and friends Eetu Kotivuori, Laith Alrahahleh, Dr. Sepul Barua, Dr. Kamrul Hassan, Dr. Parvez Rana, Dr. Ranjith Gopalakrishnan, Dr. Jinnan Gong, Dr. Pradipta Halder, Dr. Anas Zyadin, Sandra Sandar, Olalla Diáz Yáñez, Augustine Gbagir, Juhani Marttila, Yeasinur Rahman, Karthikeyan Natarajan, Syed Adnan, Dmitrii Lepilin, Mihails Cugunovs, Luis Puerto, Esa-Petteri Kauppinen, and Toni Sanio are worthy of mention. All of my friends and well-wishers, at home and abroad, inspired me to proceed with this dissertation, and all of them are remarkably appreciated. I am delighted to mention Prof. Carsten Smith-Hall, Prof. Lars Vesterdal, and Lars Holger Schmidt (Copenhagen, Denmark) and Prof. Morag McDonald, Dr. Robert Brook, and Dr. Mark Rayment (Bangor, UK), whose inspiring words and kind responses have helped me for being prolific. My special thanks to Dr. Fergus Sinclair, Dr. Tim Pagella, and Genevieve Agaba, Bangor, UK for getting me introduced with simulations-based natural resource management. My dear friends Lærke Aaboe-Jacobsen and Sidsel Fogh Thormose, Copenhagen, Denmark, who perceived my aptitude for teaching, are also notably acknowledged.

I sincerely valued the comments and suggestions of the preliminary examiners, Prof. Hardi Tullus, Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Tartu, Estonia and Risto Sievänen, Principal Scientist, Natural Resources Institute Finland, Helsinki, Finland, who meticulously reviewed the thesis.

I would like to extend my earnest gratitude to the authority of the Institute of Forestry and Environmental Sciences, University of Chittagong (IFESCU), Bangladesh for providing me with leave of absence to complete the doctoral study. All of my respected teachers, colleagues, and the staff of the IFESCU are enormously thanked for rendering their support, to help me, in multiple ways, throughout the years.

At last, though definitely not least, I cannot but remember the courageous people who have long been fighting the adverse impacts of climate change in Bangladesh.

Tarit Kumar Baul
Joensuu, June 2018

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following articles, which are referred to in the text by their Roman numerals (i.e., Paper I, II, III). Papers I and III have been reprinted with the kind permission of the publishers. Paper II is the author´s version of a submitted manuscript.

I. Baul T.K., Alam A., Strandman H., Kilpeläinen A. (2017). Net climate impacts and economic profitability of forest biomass production and utilization in fossil fuel and fossil-based material substitution under alternative forest management. Biomass and Bioenergy 98: 291–305.
https://doi.org/10.1016/j.biombioe.2017.02.007

II. Baul T.K., Alam A., Strandman H., Seppälä J., Peltola H., Kilpeläinen A. (2018). Does thinning regime affect climate impacts of forest biomass production and utilization in Norway spruce less than timber use efficiency and substitution impacts? (Manuscript in review)

III. Baul T.K., Alam A., Ikonen A., Strandman H., Asikainen A., Peltola H., Kilpeläinen A. (2017). Climate change mitigation potential in boreal forests: impacts of management, harvest intensity and use of forest biomass to substitute fossil resources. Forests 8: 455.
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Tarit Kumar Baul (Baul T.K.) was the primary author of all of these papers, and was responsible for model-based analyses and the writing of Papers I and III. The primary author performed data analysis and writing together with the co-authors of Paper II. The co-authors improved the papers by commenting on, and editing, the manuscripts.

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ABBREVIATIONS AND DEFINITIONS

Symbol/Term	Definition
a	Year
BN	Logging residues (top parts of stems, branches, and needles)
BNR	Logging residues (top parts of stems, branches, and needles), coarse roots, and stumps
CO_2	Carbon dioxide
C_{net} (Climate impact)	Net CO_2 exchange of the forest-based biosystem, based on summation of the NEE, the stock change in wood products (C_{hwp}) (inflow-outflow), the carbon emissions from the combustion of energy biomass (C_{eb}) and processing waste (C_{waste}), from management (C_{man}) and manufacturing of wood products from timber (C_{manu}), and the substitution impact (C_{subst}). Negative values of C_{net} indicate climate benefits
CCME (Climate change mitigation efficiency)	Total cumulative radiative forcing (CRF) was divided by the total amount of harvested timber, and expressed as nW m^{-3} of timber
DBH	Tree breast height diameter at final felling
DF	Displacement factor (tC tC^{-1}) for wood products, energy biomass and processing waste
EC	European Commission
EU	European Union
FF	Final felling
GHG	Greenhouse gas
ha	Hectare
I (Net climate impact)	Difference in annual net CO_2 exchange caused by emissions and sequestration between the biosystem (I_{BIO}) and the fossil system (I_{REF}). Negative values of I indicate climate benefits
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LULUCF	Land Use, Land Use Change and Forestry
Mg	Megagram (ton)
N	Nitrogen
n	Nano
NFI	National Forest Inventory
NPV	Net present value
NEE (Net ecosystem CO_2 exchange)	Difference between sequestration of CO_2 in biomass growth (C_{seq}) and emissions from decomposition of soil organic matter (C_{decomp}). Sequestration and decomposition are expressed as negative (-) and positive (+) values, respectively

RF (Radiative forcing)	The impacts of CO_2 on the atmosphere (i.e., change in the balance of incoming and outgoing energy in the Earth–atmosphere system). Negative values of RF indicate a cooling climate impact
T	Timber
t	Ton (Megagram)
UNFCCC	United Nations Framework Convention on Climate Change
W	Watt
Energy biomass	Logging residues, coarse roots, and stumps from final felling
Forest biomass	Timber and energy biomass
Fossil-based materials	Steel, concrete, plastic
Fossil energy	Coal, oil
Processing waste	Pulping (black liquor) and sawing (bark, sawdust) residues
Timber	Pulpwood and sawlogs
Timber use efficiency	The share of wood products (in %) manufactured from timber
Wood products	Pulp/paper products and sawn wood obtained from pulpwood and sawlogs, respectively

1 INTRODUCTION

1.1 Background of the study

An increase in atmospheric greenhouse gas (GHG) concentrations, particularly carbon dioxide (CO_2), is warming global climate (Intergovernmental Panel on Climate Change [IPCC] 2014a). Keeping the temperature increase below 2ºC, compared to the pre-industrial level, requires a reduction in CO_2 and other GHG emissions by 40–70% by 2050, based on 2010 concentrations, and emissions should be near zero or negative by 2100 (IPCC 2014a; UNFCCC 2015). The IPCC emphasizes an integrated strategy for climate change mitigation that involves reducing the use of fossil energy and fossil-based materials, and enhancing carbon sinks in the land use, land use change, and forestry (LULUCF) sector (IPCC 2014a, 2014b). Forests offer possible pathways for climate change mitigation through the sequestration and storage of carbon in forests and harvested biomass, and the use of harvested biomass as a substitute for fossil energy and fossil-based materials, so as to reduce atmospheric CO_2 emissions (e.g., Canadell and Raupach 2008; Lemprière et al. 2013; IPCC 2014b; Kurz et al. 2016).

The European Union's (EU) policy of climate change mitigation aims to raise the share of renewable energy to 27% and 55% in final energy consumption by 2030 and 2050, respectively, with a vision of 40% and 80–95% emissions reductions, compared to 1990 (European Commission [EC] 2011a, 2016). In the EU, an increased use of forest biomass is seen as one of the fundamental strategies for climate change mitigation (EC 2011b; EU 2015). The Nordic countries, with their extensive forest resources, are a potential source of biomass and industrial by-products (e.g., black liquor, bark, sawdust, wood chips, other wood residues) that could be used in energy generation and achieving the targets set in climate policy for climate change mitigation (Rytter et al. 2015, 2016; International Energy Agency [IEA] 2016). Currently, in Finland and Sweden, for example, timber (sawlogs and pulpwood) is widely used in the sawing, pulping, and paper industries for the manufacture of wood-based products (Gustavsson and Tullin 2014; Koponen et al. 2015; Natural Resources Institute 2017a) that act, in addition to industrial by-products, as substitutes for fossil-based materials and fossil energy (Portin et al. 2013; IEA 2016).

Finland's commitment to the EU policy of climate and energy is an 80% emissions reduction by 2050, relative to 1990 levels (Climate Change Act 609/2015, Ministry of the Environment 2015). Accordingly, it aims to raise the share of total renewable energy to 38% by 2020 and to 50–60% by 2050 (Ministry of Employment and the Economy 2014). The annual share of total renewable energy in total energy consumption was, on average, 33%, with an 80% share of forest-based renewable energy in the form of industrial by-products (65%) and energy biomass (15%) (Statistics Finland 2016). Energy biomass, in the form of small-sized stem wood, logging residues, roots/stumps (in final fellings), and small-sized trees (in early/energy wood thinnings), is being used in power generation and district heating (Koponen et al. 2015; IEA 2016). In final fellings, coarse roots and stumps are harvested, mainly from Norway spruce (*Picea abies* L. Karst) stands, and in energy wood thinnings, small-sized trees are harvested from Norway spruce, Scots pine (*Pinus sylvestris* L.), and broadleaved species stands. The annually harvested yields of timber and energy biomass were 62 and 8 million m^3, respectively, in 2016 (Natural Resources Institute 2017b). The amount of timber harvested is set to be increased by 10–30 million m^3 in the near future, however, to contribute to the Finnish bioeconomy (Ministry of Economic Affairs and Employment 2014).

Current Finnish forest management recommendations aimed at producing mainly timber (Äijälä et al. 2014) may need to be modified to potentially utilize existing forest resources to increase carbon sequestration and integrated biomass (timber and energy biomass) production for mitigating climate change (Matala et al. 2009; Routa et al. 2011a; Pyörälä et al. 2014; Hynynen et al. 2015). Over a stand rotation, carbon sequestration, stocks, and energy biomass can be increased by using higher stocking in forests than currently recommended in thinnings (Garcia-Gonzalo et al. 2007a; Nunery and Keeton 2010; Alam et al. 2012; Kilpeläinen et al. 2016a). However, the delayed thinnings, and a consequent decrease in the share of sawlogs, may decrease the economic profitability of forest production (Torssonen et al. 2016). Conversely, annual timber production could be increased by using lower thinning thresholds, regardless of species, but this may decrease carbon sequestration and stocks (Alam et al. 2008). Using short rotations of 30–60 years may increase both annual biomass production and economic profitability, but long rotations of 80–100 years may increase carbon stocks in forests (Pyörälä et al. 2012; Routa et al. 2012; Kilpeläinen et al. 2016b). Intensified biomass harvests from final fellings (timber, in addition to logging residues and stumps/roots) in Norway spruce stands decrease carbon stocks in forests (Mäkipää et al. 2015), but nitrogen fertilization increases both carbon sequestration, stocks, and biomass production, as well as the economic profitability of forest production in boreal conditions (Sathre et al. 2010; Routa et al. 2011b; Bergh et al. 2014; Hedwall et al. 2014).

The management measures required to produce the desired amount of carbon sequestration and harvestable biomass depend also on the initial conditions of the forests (e.g., age structure) (Garcia-Gonzalo et al. 2007b; Alam et al. 2010; Malmsheimer et al. 2011; Eliasson et al. 2013), and may have subsequent effects on the timing of the climate impacts of biomass production and utilization (Kilpeläinen et al. 2016a, 2017; Zubizarreta Gerendiain et al. 2016). Carbon sequestration is highest in middle-aged stands and lowest in mature stands, which is opposite to timber production. The highest timber yields for a landscape consisting of Norway spruce and Scots pine stands have been found over a 100-year study period when the initial age structure was dominated by mature stands (Garcia-Gonzalo et al. 2007b). A landscape consisting of Norway spruce, and initially dominated by middle-aged stands, produced the lowest CO_2 emissions for energy biomass, in comparison to using coal, when using a 120-year rotation (Routa et al. 2012), whereas a landscape dominated initially by young stands produced the lowest CO_2 emissions when using 60–80-year rotations (Routa et al. 2012; Kilpeläinen et al. 2017). The interactive effects of forest management and initial conditions on the climate impacts of biomass production and utilization (Mitchell et al. 2012; Kilpeläinen et al. 2017) can be studied by applying model simulations. These offer the means to study the development of carbon sequestration, forest carbon stocks, and timber and energy biomass production over any given study period (Hynynen et al. 2015; Heinonen et al. 2017; Pilli et al. 2017).

The utilization of wood products (e.g., sawn wood and pulp/paper products) mitigates climate change by avoiding carbon emissions from the use of fossil-based materials (e.g., concrete, steel and plastic) (Gustavsson et al. 2006, 2017; Eriksson et al. 2007; Lundmark et al. 2014; Smyth et al. 2017a). The retention of carbon in the wood products depends on the type of product and its lifespan (Pingoud et al. 2010; Werner et al. 2010). The substitution impacts of using wood products and energy biomass depend on the timing of their entry into the technosystem (Gustavsson and Sathre 2011; Sathre and Gustavsson 2011, 2012; Mitchell et al. 2012; Lundmark et al. 2014; Smyth et al. 2017a, 2017b). For example, the combustion of energy biomass produces an instantly higher amount of carbon emissions per energy unit than that of fossil fuels (Repo et al. 2012, 2015a; Gustavsson et al. 2015), and may therefore have a lower substitution potential than the use of wood products to replace fossil-based products (Pingoud et al. 2010; Jasinevičius et al. 2015; Kilpeläinen et al. 2016a). The climate impacts of using wood products also vary, however, depending on the differences in emissions of the substituted materials and the functional unit used in the study of these (Sathre and O′Connor 2010; Ter-Mikaelian et al. 2015a; Smyth et al. 2017a).

Displacement factors (i.e., one ton of fossil carbon emissions avoided per ton of carbon used in wood products, tC tC^{-1}) are used to evaluate the substitution impacts of using wood products in place of fossil-based materials and fuels (Schlamadinger and Marland 1996). A wide range of displacement factors can be found in previous reviews of wood products; for example, 0.25 to 5.6 (Geng et al. 2017) and -2.3 to 15.0 (Sathre and O′Connor 2010), which varied with differences in application (e.g., wood vs steel, wood vs concrete) and the final wood products (Werner et al. 2005; Knauf et al. 2015; Cintas et al. 2016). The magnitude of displacement factors also depends on the development of new wood products that substitute for fossil-based materials (Werner et al. 2015; Rüter et al. 2016; Suter et al. 2017).

Life cycle assessments (LCAs) can be used to study the climate impacts of forest biomass production and biomass utilization (Kilpeläinen et al. 2011; Ter-Mikaelian et al. 2015b). All of the emissions and sequestration of carbon can be studied by means of an attributional LCA (ALCA) in a biosystem, whereas the consequential LCA (CLCA) considers both the direct and indirect impacts between the compared systems through time (Cherubini et al. 2011; Lippke et al. 2011; Kilpeläinen et al. 2012; Plevin et al. 2013; Ter-Mikaelian et al. 2015b). The results from LCAs vary due to the different temporal and spatial (e.g., stand, landscape, regional scale) system boundaries set for each study, and different assumptions made in the calculations (Helin et al. 2013; Buchholz et al. 2014, 2016; Klein et al. 2015). The timing of emissions and sequestration of carbon affect the climate impacts of energy biomass and wood products (e.g., Sathre et al. 2010; Sathre and Gustavsson 2011, 2012; Kilpeläinen et al. 2012, 2017; Cherubini et al. 2013). Therefore, climate impact assessments that include the temporal dynamics of carbon exchange can be studied by using different time periods (McKechnie et al. 2011; Helin et al. 2016). When a dynamic forest-based biosystem is compared to the fossil system, the forest land use option in the fossil system should also be quantified (Haus et al. 2014).

1.2 Aims of the study

In this work, the main aim was to investigate the climate impacts of carbon sequestration in forests, and the substitution of fossil energy (e.g., coal and oil) and fossil-based materials (e.g., concrete, steel and plastic) with forest biomass (energy biomass, pulpwood and sawlogs) under the boreal conditions in Finland. The study was conducted under varying forest management scenarios at stand, landscape and regional levels. The specific objectives were:

(i) to investigate the net climate impact and economic profitability of biomass production and utilization in fossil fuel and fossil-based materials substitution in a Norway spruce stand under alternative forest management over 60–100-year rotations (Paper I);

(ii) to analyze whether the thinning regime affects the climate impacts of forest biomass production and utilization less than timber use efficiency and substitution impacts in Norway spruce forest areas with alternative initial age structures over a 80-year period (Paper II); and

(iii) to investigate the impacts of alternative forest management scenarios and harvest intensities on the climate impacts of forest biomass production and utilization in southern Finland over a 40-year period (Paper III).

2 MATERIALS AND METHODS

2.1 System boundaries of the study

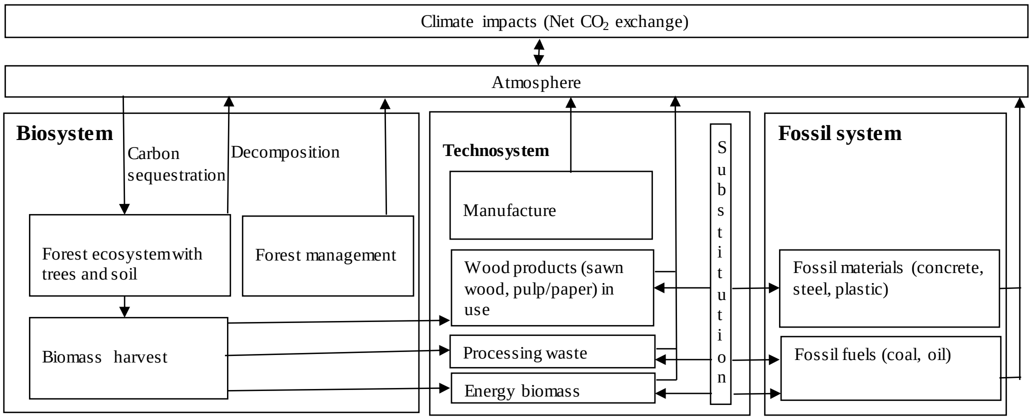

Figure 1 System boundaries of the study.

Figure 1 shows the system boundaries, with flows of carbon in the forest-based biosystem and technosystem when forest biomass replaces fossil-based materials and energy in the fossil system. In Paper I, the climate impacts of forest biomass production and utilization were calculated by employing the CLCA, and were expressed as a difference in net CO_2 exchanges (C_{net}) between the biosystem and fossil system. In Papers II and III, an ALCA was used. The C_{net} included carbon sequestration in the growth of trees, emissions from soil decomposition, emissions from the combustion of processing waste (Papers I–III) and energy biomass (Papers I, III), emissions from forest management operations, and from the manufacturing of final wood products (Papers I, II). The change in the wood product stocks in use was also considered (Papers I–III). The substitution impacts of forest biomass were quantified by using displacement factors (tC tC^{-1}; Papers II, III). The climate impacts were calculated under alternative management (Papers I–III) and harvesting scenarios (Papers I, III).

The modelling work strictly obeyed the management scenarios, and therefore, the potential of produced biomass in substituting for fossil materials and fossil fuels should be considered as a maximum biological potential. The modelling work was conducted at the stand level, with a mature stand as a starting point (Paper I), at the landscape level, under alternative initial forest age structures (Paper II), and at the regional level (Paper III), for various study periods and rotations. The effects of alternative management and harvesting scenarios in the biosystem were used to study the sensitivity of climate impacts to the changes in the biomass production (Papers I-III). In Paper I, alternative reference managements in the fossil system were used to study the sensitivity of climate impacts to indirect impacts of biomass production and utilization.

2.2 Outlines of the models used

2.2.1 SIMA ecosystem model

A gap-type forest ecosystem model (SIMA) (Kellomäki et al. 2005, 2008) was utilized to simulate the net ecosystem CO_2 exchange (NEE), and production of timber (pulpwood and sawlogs) and energy biomass, in Papers I–III. The NEE refers to the balance between carbon sequestration in growth (above- and below-ground living biomass) and carbon emissions from decaying soil organic matter (humus and litter).

In the SIMA model, the growth and development of a tree stand are simulated under the influences of the temperature sum (+5˚C), sunlight availability, soil moisture, nitrogen availability, atmospheric CO_2 concentration, and forest management. The growth of a single tree is based on stem diameter growth at breast height (1.3 m above ground level), and is a product of potential diameter growth and species-specific multipliers for environmental factors.

The dynamics of the forest ecosystem is determined by the number and mass of trees as a function of their regeneration, growth, and death, based on the availability of resources. Trees may die either due to competition for resources or randomly. In addition to dead trees, the litter from different components of living trees (foliage, branches, and fine roots) are decomposed in the soil system and converted to humus. The decomposition rate of litter and humus is dependent on evapotranspiration and the chemical components content (nitrogen, lignin, and ash) of the litter and humus. The decomposition of humus controls the mineralization of nitrogen, which makes nitrogen bound in humus available for tree growth.

Management includes planting of a given species at a desired spacing, thinning, nitrogen fertilization, final felling, and a varying length of rotations. Timing and frequency of thinning over a rotation are determined based on the thresholds for a basal area (cross-sectional area of stems of all trees in a stand), which are a function of the dominant height of the trees (i.e., the average heights of the 100 tallest trees) in the stand. Whenever a given upper threshold for the basal area is reached, at a given dominant height, thinning is triggered, and the basal area is reduced to the recommended level. In harvesting, timber production is considered in thinnings and final fellings. Pulpwood includes logs with a top diameter of 6.5 to <17 cm, and sawlogs include logs with a top diameter of 17 cm and above. Energy biomass denotes for logging residues (the tops of stems not suitable for timber, branches, and needles) and coarse roots, and stumps that were harvested in final fellings.

2.2.2 Life cycle assessment (LCA) tool

The LCA tool utilized the SIMA model outputs (i.e., the NEE, and timber and energy biomass yields) to estimate annual net CO_2 exchange (C_{net}, g CO_2 m^2 a^{-1}), as caused by all the main phases included in forest production and biomass utilization in substitution of fossil-based materials and fuels (Kilpeläinen et al. 2011; Alam et al. 2017). In addition to NEE, the C_{net} included CO_2 emissions from the forest management, manufacturing of wood products from timber, the degradation of wood products, and combustion of energy biomass and of the processing waste of timber (Papers I–III). The annual stock change in wood products (Papers II, III) was calculated as the annual difference between inflow of wood products into the technosystem and outflow of wood products (emissions from degradation) (Karjalainen et al. 1994). The substitution impacts were quantified by using product-specific displacement factors (Papers II, III), the default values of which were 0.5, 1, and 2 for processing waste/energy biomass, pulp/paper products, and sawn wood (tC tC^{-1}), respectively (Schlamadinger and Marland 1996; Sathre and O´Connor 2010;

Geng et al. 2017). In addition, the timber use efficiency (a proportion of roundwood used for wood products) was also used in the calculation of the C_{net} (Paper II).

The LCA tool considers C_{net} as giving negative (-) values when CO_2 flow was from the atmosphere into the ecosystem, and positive (+) values for the reverse direction of CO_2 flow. The values for carbon sequestration in growth, increasing stock in wood products, and substitution benefits were considered to be negative (-). The C_{net} was further used to calculate radiative forcing (RF, nW m^{-2}; Ramaswamy et al. 2001) (Paper II) to quantify the impacts of forest biomass production and utilization on atmospheric CO_2 concentrations (Kilpeläinen et al. 2012).

2.3 Management and harvesting scenarios of model-based simulations

In Paper I, the effects of forest management on the net climate impacts of forest biomass production and utilization in fossil fuel (coal and oil) and fossil-based material (concrete, steel and plastic) substitution were investigated in a Norway spruce stand on a medium fertile site in central Finland (Joensuu region) over 60–100-year rotations (Table 1). In the simulations, current business-as-usual Finnish forest management recommendations for thinning, aimed at producing timber (Äijälä et al. 2014) and maintaining an initial stand density of 2,500 stems ha^{-1}, were used as a baseline. Alternative management scenarios included 10–30% higher or lower stocking in thinnings than in the baseline, and/or nitrogen fertilization (150 kg N ha^{-1} in thinnings). Harvest intensities included harvesting of only timber and timber with logging residues, coarse roots, and stumps in final fellings (Table 1). For the net climate impact calculations, either baseline or unthinned scenarios of the biosystem were used as a reference management in the reference fossil system. In addition, the fossil system was considered without the NEE of CO_2 (Paper I).

In Paper II, the effects of the thinning regime, substitution impacts, and timber use efficiency on climate impacts of biomass production and utilization were analyzed in model forest areas in central Finland (Joensuu region) over a 80-year period (Table 1). The area consisted of 80 pure Norway spruce stands on a medium fertile site type, and it had alternative initial age structures at the beginning of the simulations (Table 1). The initial age structures of the forest area were: i) right-skewed (mostly young stands); ii) normally distributed (mostly middle-aged stands); and iii) left-skewed (mostly mature stands). The current business-as-usual thinning recommendations to produce timber (Äijälä et al. 2014) were used as a baseline. Alternative thinning regimes included 20% higher or lower stocking in thinnings than in the baseline. Only timber was harvested in the thinnings and final fellings (Table 1).

In Paper III, the climate impacts of forest biomass production and utilization were investigated in southern Finland (old Forest Centre Units 1–10). The effects of alternative forest management scenarios and harvest intensities were studied in three sub-regions (namely southern, western, and eastern Finland) over a 40-year period (2016–2055), using the 10th (2004–2008) National Forest Inventory (NFI) forest data for upland mineral soils as input for the simulations (Table 1). Forest site fertility ranged from poor (CT) to fertile (OMT) site types (Table 1). The current business-as-usual thinning recommendations to produce timber (Äijälä et al. 2014), and a final felling made at a tree breast height diameter (DBH) of 26 cm, were used as a baseline. Alternative management scenarios included 20% higher or lower stocking in thinnings than in the baseline, and the use of final felling made at a DBH of 22 cm (Table 1). In alternative harvest intensities, logging residues, with and without coarse roots and stumps, were harvested, in addition to the timber in the final fellings (Table 1).

Table 1 Parameters and methods used in the simulations and forest management scenarios used in Papers I–III. T = only timber, T+BN = timber and logging residues, T+BNR = timber, logging residues, coarse roots, and stumps.

Parameter/method	Paper I	Paper II	Paper III
Simulation location	Middle boreal zone, central Finland, Joensuu (62°39'N, 29°37'E)	Middle boreal zone, central Finland, Joensuu (62°39'N, 29°37'E)	Southern Finland (between 60° and 64° N)
Simulation approach	Stand level	Landscape level	Regional level
Tree species	Norway spruce	Norway spruce	Norway spruce, Scots pine, birch
Forest site type	Medium fertile (MT)	Medium fertile (MT)	All site fertility types (CT, VT, MT, OMT)
Initial data	Mature stand	Age structures (normal-, right-, left-skewed)	10th NFI
Initial stand density (seedlings ha^{-1})	2,500	2,000	2,000 (Norway spruce, Scots pine), 1,600 (birch)
Pulpwood top diameter (cm)	6.5 to <17	6.5 to <17	6.5 to <17
Sawlog top diameter (cm)	≥17	≥17	≥17
LCA method	Consequential	Attributional	Attributional
Management scenarios			
Business-as-usual management (baseline)	Yes	Yes	Yes
Unthinned (as a reference)	Yes	No	No
Increase in stocking in thinning (%)	± 10, 20, and 30	± 20	± 20
Nitrogen fertilization (kg N ha^{-1})	150 kg in thinning years	No	No
Timing of final felling (FF)	Fixed rotation length	Fixed rotation length	FF done at DBH 26/22 cm
Simulation time (years)	60, 80, and 100	80	40 (2016–2055)
Harvest intensity			
Harvest of timber (in thinning and final felling) and energy biomass (in final felling)	T T+BNR	T	T T+BN T+BNR

2.4 Analysis of simulation outputs

The effects of alternative forest management and harvesting scenarios on forest biomass (pulpwood, sawlogs, and energy biomass) yield were calculated over the study period (Table 2; Papers I, III). The economic profitability of biomass production was quantified, based on the net present value (NPV, 3% interest rate) under alternative forest management scenarios, and in different sub-regions (Table 2; Papers I, III). Additionally, in Paper I, the sensitivity of the annual NPV to variable interest rates (2% and 4%) was analyzed (Table 2).

The climate impacts were analyzed at stand level (Paper I), landscape level (Paper II), and regional level (Paper III) under alternative forest management and/or harvesting scenarios (Tables 1, 2). The effects of forest management and/or harvesting scenarios on the NEE, and the substitution impacts of using biomass and carbon stock changes in wood products, were analyzed annually (Paper II), and over the study period or varying rotation periods (Papers I, III) (Table 2). In Paper II, the climate impact was calculated for the 80-year study period, and expressed as cumulative radiative forcing (CRF, nW m^{-2}). It was also used to calculate the climate change mitigation efficiency (CCME, nW m^{-3}) (Braun et al. 2016) of the biomass production and utilization (Table 2).

The sensitivity of climate impacts to the varying displacement factors used in substitution was analyzed by changing the default values (0.5, 1, and 2) of the displacement factors (tC tC^{-1}) for energy biomass and/or processing waste, pulp/paper products, and sawn wood, respectively (Papers II, III). In the analysis, the default displacement factors were doubled (to 1, 2, and 4) (Papers II, III), halved (0.25, 0.5, and 1) (Paper II), and lowered (0, 0.5, and 1) (Paper III) for the respective components of the biomass. The sensitivity of climate impacts to timber use efficiency was also analyzed by increasing/decreasing the default efficiency (i.e., 50% of wood products). High efficiency denoted a 70% use of wood products and low efficiency denoted a 30% use of wood products (Paper II).

Table 2 Included parameters, with units, for calculations used in Papers I–III. t = ton (i.e., Megagram, Mg).

Parameter	Paper I	Paper II	Paper III
Sawlog yield	m^3 ha^{-1} a^{-1}	m^3 ha^{-1} a^{-1}	Mg ha^{-1} a^{-1}
Pulpwood yield	m^3 ha^{-1} a^{-1}	m^3 ha^{-1} a^{-1}	Mg ha^{-1} a^{-1}
Energy biomass yield	t ha^{-1} a^{-1}	–	Mg ha^{-1} a^{-1}
Processing waste	t CO_2 ha^{-1} a^{-1}	g CO_2 m^{-2} a^{-1}	Mg ha^{-1} a^{-1}
Net present value (NPV)	€ ha^{-1} a^{-1} (2–4% interest rates)	–	€ ha^{-1} (3% interest rate)
Net ecosystem CO_2 exchange (NEE)	t CO_2 ha^{-1} a^{-1}	g CO_2 m^{-2} a^{-1}	Mg CO_2 ha^{-1} a^{-1}
Climate impact (C_{net})	t CO_2 ha^{-1} a^{-1}	g CO_2 m^{-2} a^{-1}, g CO_2 m^{-2}	Mg CO_2 ha^{-1} a^{-1}
Substitution impacts	t CO_2 ha^{-1} a^{-1}	g CO_2 m^{-2} a^{-1}	Mg CO_2 ha^{-1} a^{-1}
Annual stock change in wood products	t CO_2 ha^{-1} a^{-1}	g CO_2 m^{-2} a^{-1}	Mg CO_2 ha^{-1} a^{-1}
Cumulative radiative forcing (CRF)	–	nW m^{-2}	–
Climate change mitigation efficiency (CCME)	–	nW m^{-3}	–

3 RESULTS

3.1 Effects of forest management on biomass yield and the economic profitability of forest production

In Paper I, maintaining 10–30% lower stocking, compared to the baseline (with timber harvest), increased mean annual pulpwood yields by up to 15% and decreased sawlog yields by up to 17% under 60–100-year rotations (30% lower stocking under 60-year rotation as an exception). Maintaining 10–30% higher stocking, compared to the baseline, increased mean annual sawlog yields and decreased pulpwood yields under 80–100-year rotations (60-year rotation as an exception). Nitrogen fertilization with lower stocking increased pulpwood yields by up to 14%, but it could not increase sawlog yields, in comparison with the baseline. Nitrogen fertilization alone, and simultaneously with higher stocking, increased the mean annual sawlog yield by up to 6%, compared to the baseline. The mean annual yield of energy biomass (logging residues, together with coarse roots and stumps) increased by up to 46% by maintaining higher stocking, compared to baseline (with energy biomass harvest), and applying nitrogen fertilization, and combining both under all rotations. In general, the highest mean annual yields of pulpwood and energy biomass resulted over a 60-year rotation, and the highest annual yields of sawlogs resulted over 80–100-year rotations (Paper I).

At the regional level (Paper III), maintaining 20% lower stocking produced higher yields of sawlogs and pulpwood (by up to 80% and 48% higher, respectively), during the initial two decades of the 40-year (2016–2055) study period, compared to the baseline. In the last two decades, the yields of sawlogs and pulpwood decreased mostly in the final 10-year period (by up to 38% and 15% lower, respectively), compared to the baseline. Maintaining higher stocking also decreased sawlog yields in the last two decades, and increased pulpwood yields in the final 10-year period. Maintaining lower stocking resulted in higher energy biomass yields during the initial two decades, but produced lower yields during the last two decades. Maintaining higher stocking increased energy biomass yields during the last two decades of the study period (Paper III).

At the regional level (Paper III), mean annual total biomass (pulpwood, sawlogs, and energy biomass together) yields over the 40-year study period increased by up to 61% by maintaining lower stocking, compared to the baseline. The final felling made at a DBH of 22 cm resulted in higher total biomass yields than that of the final felling made at a DBH of 26 cm. Biomass yield was, on average, higher in the southern and eastern sub-regions than in the western one (Paper III).

In general, producing timber (pulpwood and sawlogs) together with energy biomass (logging residues, with coarse roots and stumps) provided higher mean annual economic profitability (NPV, interest rates 2–4%), compared to the baseline with only a timber harvest (30% higher stocking as an exception) (Paper I). The NPV (with a default interest rate of 3%), over 60-, 80-, and 100-year rotations, increased by up to 14, 12, and 11%, respectively, compared to the baseline (Paper I). The corresponding ranges of increasing NPV with 2% and 4% interest rates were 11–21%, 10–18%, and 8–18% for the rotations, respectively. On average, the highest NPV was gained by maintaining 10–30% lower stocking than the baseline and nitrogen fertilization simultaneously (Paper I); however, with a 2% interest rate, maintaining lower stocking associated with production of both timber and energy biomass together decreased NPV over a 100-year rotation (Paper I).

At the regional level (Paper III), producing timber together with energy biomass provided higher NPV (interest rate of 3%), compared to the baseline, over the 40-year study period (20%

higher stocking under final felling made at a DBH of 26 cm as an exception). Maintaining 20% lower stocking produced higher NPV, compared to the baseline, and up to 30% higher NPV resulted when final felling was made at a DBH of 22 cm. NPV was, on average, higher in the southern and eastern sub-regions than in the western one (Paper III).

3.2 Climate impacts of carbon sequestration and the substitution of fossil materials and energy

Maintaining lower stocking (Papers I–III), compared to the baseline, and final felling made at a DBH of 22 cm (Paper III) decreased both net carbon sequestration and climate impacts (Table 3). Maintaining higher stocking (Papers I–III) and using nitrogen fertilization (Paper I), which could enhance net carbon sequestration, also increased the climate impacts (lower absolute values), compared to the baseline (Table 3). At the landscape level, higher stocking also increased climate impacts in all of the initial age structures (Table 3), and the climate impacts were down to -33.5 nW m^{-2} over the 80-year study period (Paper II). At the regional level (Paper III), climate impacts over the 40-year study period were the greatest under final felling made at a DBH of 26 cm (Table 3), and the contribution of the net carbon sequestration to total climate impact was between 7 and 25%, depending on the management scenario (Paper III).

The substitution impacts of using wood products (sawn wood and pulp/paper products), and processing waste (Papers I–III) and energy biomass (Papers I, III) generated climate benefits. The larger share of sawlogs in higher stocking, compared to that in the baseline, enhanced the climate benefits over the 80–100-year rotations (Paper I). Contrarily, a larger share of pulpwood than sawlogs in lower stocking produced the lowest substitution impacts, especially over the 60-year rotation (Paper I). An increased production of pulpwood and sawlogs also enhanced the cumulative climate impacts during the initial two decades of the 80-year study period in the initially left-skewed age structure at landscape level (Paper II). This was opposite to the right-skewed age structure, in which a high initial growth rate increased annual climate impacts in the initial half of the study period. The greatest cumulative climate impacts were finally generated in the initially right-skewed age structure, due to cumulative substitution impacts and the lowest emissions from the stock change of wood products (Paper II).

At the regional level (Paper III), the substitution impacts of using timber began from the start of the 40-year study period, and accumulated during the initial two decades, when higher amounts of sawlogs and pulpwood entered the technosystem, in the case of lower stocking under final felling made at a DBH of 22 cm, compared to the baseline. Additionally, a larger share of sawlogs than pulpwood in lower stocking generated higher substitution impacts, compared to the baseline over the study period. The substitution impacts were most enhanced when final felling was made at a DBH of 22 cm (Paper III). The contributions of the substitution impacts, and the increase of carbon stock in sawn wood and pulp/paper products to climate impacts, were 33–43%, 10–15%, and 7–15%, respectively, depending on the management over the study period. Both the substitution impacts and climate impacts were greater in the southern and eastern sub-regions, compared to the western one (Paper III).

The harvesting of timber, together with logging residues, coarse roots, and stumps, increased the climate impacts (Papers I, III), compared to harvesting only timber in the final fellings (Table 3). Energy biomass production with timber initially caused higher emissions, compared to the use of fossil counterparts; however, over the rotation, the use of energy biomass with timber production generated climate benefits against the fossil counterparts (Paper I).

The climate impacts were also affected by the reference management used in the fossil system (Paper I). The greatest climate benefits were found over 80–100-year rotations, when using the baseline as a reference, as opposed to over a 60-year rotation using unthinned as a reference. When the fossil system was considered without the NEE of a forest stand, all the management scenarios and rotations (60–100 years) provided greater climate impacts, compared to the other two references (Paper I).

3.3 Sensitivity of climate impacts to displacement factors and timber use efficiency

In Paper II, the doubled displacement factors (1, 2, and 4 tC tC^{-1}) produced 114% greater cooling climate impacts (negative CRF) when maintaining 20% higher stocking, compared to the baseline with default factors. Halved factors (0.25, 0.5, and 1 tC tC^{-1}) produced 64% lower cooling climate impacts when maintaining 20% lower stocking, compared to the baseline with default factors. Both these greatest and least cooling climate impacts were found under the initially left-skewed age structure over the 80-year study period. Similarly, with the high (70% of wood products) and low (30% of wood products) timber use efficiency, the cooling climate impacts when maintaining 20% higher or lower stocking were 59% higher and 61% lower, compared to the baseline with default timber use efficiency, respectively, under the same initial age structure (Table 3) (Paper II).

The highest and lowest CCMEs over the 80-year study period were found in higher stocking with doubled displacement factors, and lower stocking with halved factors, respectively (Paper II). However, the CCME of maintaining higher stocking was higher, compared to the substitution impacts, between years 2 and 46, depending on the initial age structures. In general, the magnitude of the CCME was greater in the initially right-skewed and normal age structures, compared to the left-skewed age structure, when using the default and halved factors. However, the greatest CCME over the whole study period was found in the initially left-skewed age structure when using higher stocking with doubled factors, which was 125% greater, compared to the baseline with default factors (Paper II). Similarly, the management scenarios with high and low timber use efficiency followed a trend similar to the case of the displacement factors, although with a smaller magnitude of CCME (Paper II).

In Paper III, the use of doubled (1, 2, and 4 tC tC^{-1}) displacement factors increased climate impacts up to 84%, and the use of lower factors (0, 0.5, and 1 tC tC^{-1}) decreased it up to 58% over a 40-year study period. Doubled displacement factors produced the greatest climate impacts when maintaining 20% higher stocking under final felling made at 22 cm, and harvesting timber together with logging residues, coarse roots, and stumps. Lowered factors produced the lowest climate impacts when maintaining 20% lower stocking under final felling made at 26 cm, and harvesting timber only. The relative contribution of the substitution impacts to the climate impacts shifted up to 60% and down to 22% when the default displacement factors were doubled and lowered, respectively. The use of variable displacement factors, as a consequence, led to changes in the relative contributions of net carbon sequestration (NEE) and carbon stock of sawn wood and pulp/paper products to the total climate impacts (Paper III).

Table 3 Relative change (%) in climate impact under alternative management scenarios and harvest intensities, compared to the baseline with timber harvest in Papers I–III. + = positive, - = negative impact, ↔ = no change in climate impact, compared to that of the baseline. Relative increases (%) are denoted as follows: in Paper I, 1–100% = +, 101–200% = ++, and 201–300% = +++; in Paper II, 1–50% = +, 51–100% = ++, and 101–150% = +++; in Paper III, 1–4% = +, 5–8% = ++, and 9–12% = +++. The same ranges also corresponded to the relative decreases (%). T = only timber, T+BN = timber and logging residues, T+BNR = timber, logging residues, coarse roots, and stumps, DF = displacement factor, FF = final felling, DBH = tree diameter at breast height. *In Paper I, climate impact denotes net climate impact averaged over three rotations (60, 80, 100 years).

Harvest intensity	% changes compared to baseline (T)											
Paper I	Management scenarios											
	Higher stocking (%)						Lower stocking (%)					
	Without fertilization			With fertilization			Without fertilization			With fertilization		
	10	20	30	10	20	30	10	20	30	10	20	30
T	++	++	++	++	++	++	-	-	-	-	-	-
T+BNR	++	++	+++	+++	+++	+++	+	-	-	+	+	+

Harvest intensity		% changes compared to baseline (T)									
Paper II		Management scenarios									
		20% higher stocking					20% lower stocking				
	Initial age structure	Default values	Doubled DF	Halved DF	High efficiency	Low efficiency	Default values	Doubled DF	Halved DF	High efficiency	Low efficiency
T	Normal	+	++	-	++	-	-	++	- -	+	- -
	Right-skewed	+	++	-	+	-	-	++	-	+	-
	Left-skewed	+	+++	-	++	-	-	+++	- -	+	- -

Harvest intensity		% changes compared to baseline (T)			
Paper III		Management scenarios			
		20% higher stocking		20% lower stocking	
		FF at DBH (cm)		FF at DBH (cm)	
	Sub-regions	26	22	26	22
T	South	+	↔	- -	- -
	West	+	↔	- - -	- - -
	East	+	↔	- - -	- - -
T+BN	South	+	↔	- -	- -
	West	+	-	- - -	- - -
	East	+	+	- - -	- - -
T+BNR	South	+	+	- -	- -
	West	+	+	- -	- -
	East	+	+	- -	- -

4 DISCUSSION AND CONCLUSIONS

4.1 Evaluation of the modelling approaches

This study aimed to investigate the climate impacts of carbon sequestration in forests, and the substitution of fossil energy (e.g., coal and oil) and fossil-based materials (e.g., concrete, steel, and plastic) with harvested biomass (energy biomass, pulpwood, and sawlogs) under Finnish boreal conditions, using varying forest management and harvesting scenarios. The implications of forest management and harvest intensity in the final felling were studied, in terms of how this would affect the climate impacts and economic profitability of biomass production. The study was undertaken at stand, landscape, and regional levels by integrating forest ecosystem model simulations (SIMA) and a LCA tool. The impacts of climate change on carbon sequestration in forests and consequent effects on mitigation were excluded from the analysis.

The LCA tool (Kilpeläinen et al. 2011) has previously been used to study the C_{net} of forest biomass production and utilization, inside and outside forest ecosystems (Routa et al. 2011a; Alam et al. 2012, 2013, 2017; Kilpeläinen et al. 2012, 2014, 2016b; Torssonen et al. 2016). In this work, the ALCA (Papers II, III) utilized all the flows of ecosystem and technosystem carbon in calculating C_{net} for management and harvesting scenarios. The CLCA (Paper I) was used to study both the direct and indirect impacts of biomass production and utilization on climate impacts, starting from a mature stand, with alternative reference managements in the fossil system. The tool enabled assessment of the climate impacts of forest biomass production and utilization in substituting for fossil-based materials and energy, for different time periods and initial conditions of forests. Radiative forcing (Paper II), calculated based on the C_{net}, provided a further assessment of the time dynamics of the climate impacts, based on the change in atmospheric CO_2 concentrations.

The performance of the SIMA model (Kellomäki et al. 2005, 2008) has been previously documented (Kellomäki et al. 2008; Routa et al. 2011a), and the simulated growth from that was in agreement with the measured volume growth, based on NFI data of permanent sample plots in Finland. The simulated growth data of the SIMA model showed a good correlation with that of the empirical growth and yield model, Motti, in the case of volume growth in Norway spruce and Scots pine (Routa et al. 2011a). Moreover, simulated data regarding the response in growth of Norway spruce to nitrogen fertilization is in good agreement with the measured data derived from long-term experiments (Mäkipää et al. 1998).

4.2 Effects of forest management on biomass yield, and the economic profitability of forest production

At the stand and regional levels, changes in thinning intensity (higher/lower stocking in thinning) (Papers I, III), nitrogen fertilization (Paper I), earlier final felling (Paper III), and intensified harvest in final felling (Papers I, III) could increase the mean annual biomass yield, compared to the baseline, but the effects of management on the yield of biomass components (e.g., pulpwood and sawlogs) varied among the management scenarios. For example, maintaining lower stocking, compared to baseline, resulted in higher annual pulpwood yields, but the annual yield of sawlogs was the highest when higher stocking, compared to baseline, was maintained in combination with nitrogen fertilization and using long rotations (80–100 years) (Paper I).

Maintaining lower stockings and intensifying biomass harvesting were able to increase economic profitability (NPV), compared to the baseline, due to earlier income from thinning, and additional income from energy biomass (Paper I), as also shown by previous studies (Routa et al. 2011b, 2012; Zubizarreta Gerendiain et al. 2016). In absolute terms, the NPV (default interest rate 3%) increased by up to 5 € ha^{-1} a^{-1} with lower stocking, compared to the baseline (Paper 1). This was also the case at the regional level (Paper III), but the values were about three times higher than those obtained at the stand level, especially when 20% lower stocking was used. This was mainly because of using a short study period (i.e., 40 years) in the regional analysis. Other reasons may include tree species and site fertility, which differed between stand- and regional-level studies, and affected the NPV considerably (Routa et al. 2011b; Hedwall et al. 2014). Although higher stocking delayed harvest and income, it was found that maintaining up to 20% higher stocking with an intensified biomass harvest could increase NPV by up to 3 € ha^{-1} a^{-1}, compared to the baseline (Paper I), mainly due to the additional income generated from increased yields of sawlogs. Also, at the regional level, maintaining 20% higher stocking increased NPV, compared to the baseline, when earlier final felling was performed, but later final felling decreased NPV, owing to lower incomes from decreased and delayed timber yields, compared to the baseline (Paper III).

The use of a higher interest rate (e.g., 4%) tended to favor shorter rotation over long rotation, because the higher interest rate has a smaller effect on future costs and income, thus it decreases the present value of the forests (e.g., Brukas et al. 2001; Grege-Staltmane and Tuherm 2010; Repo et al. 2015b). In this study, using 2–4% interest rates, the annual NPV was found to be generally higher when using short rotations (60 years) compared to long rotations of 80–100 years (Paper I). This was due to earlier income from the timber and energy biomass (Routa et al. 2012). In the case of long rotations, the income from increased yields of sawlogs, due to fertilization, could not be compensated for by the costs associated with fertilization (up to four applications) under an increased rate of interest (e.g., 3–4%). This was contrary to the case of the short rotations with a high interest rate, in which the costs for fertilization (up to two applications) decreased and the NPV from timber increased over the studied period (Paper I).

4.3 Climate impacts of biomass production and utilization

The climate impacts of biomass production and utilization were decreased by maintaining lower stocking in forests (Papers I–III), and making final fellings earlier (Paper III), compared to the baseline (Table 3). This was caused by decreased net carbon sequestration and increased decay of logging residues from earlier thinnings and final fellings (Kallio et al. 2013; Mika and Keeton 2015; Noormets et al. 2015). Maintaining higher stocking, on the other hand, increased net carbon sequestration in forests and enabled the logging residues to decay later, due to delayed thinnings, eventually increasing the climate impacts, compared to the baseline (Table 3) (Papers I–III). Nitrogen fertilization with higher stocking increased the climate impacts further (Paper I), but using up to 20% higher stocking and an earlier final felling may be the best option to increase both the climate impacts and economic returns, compared to the baseline (Papers I, III). Previously, it has been suggested that cost-effective climate benefits of forest biomass could be generated by increasing the growing stock of forests (Richards and Stokes 2004; Eriksson 2015; Vass and Elofsson 2016).

Generally, young forest landscapes have the potential to increase the climate benefits of the biosystem, when harvested wood products and energy biomass are used for substitution of fossil-based materials and fuel (e.g., Hennigar et al. 2008; Gustavsson and Sathre 2011). In the initially right-skewed (mostly young) and normal (mostly middle-aged) forest age structures, it was found that using higher stocking increased the net carbon sequestration and climate impact most, i.e., by up to 8 and 11%, respectively, compared to the baseline (Paper II). A regional study (Paper III) revealed a similar trend. For example, forests in the southern and eastern sub-regions in Finland, consisting mainly of younger stands (Ylitalo 2014), increased climate impacts by up to 34%, compared to that in western sub-regions.

The substitution impacts were generally higher when using 80–100-year rotations, compared to a 60-year rotation, due to the increased production of sawn wood (Paper I). A previous study has also found the greatest climate impacts of forest biomass over long rotations (ca. 100 years) in Norway spruce forest, with increased sawlog production for fossil-based material substitution (Pingoud et al. 2010). At the landscape level (Paper II), both the substitution impacts and the lowest emissions from wood product stocks produced the greatest climate impacts in the last half of the 80-year study period for a right-skewed age structure. Conversely, in an initially left-skewed age structure, the substitution impacts and increased stocks of wood products compensated for the impacts of decreasing net carbon sequestration, and caused the greatest cumulative climate impacts in the initial two decades of the study period (Paper II). This was also the case during the initial two decades of the 40-year study period in a regional-level analysis, when the stock of wood products increased and the substitution impacts accumulated forward from the increased amount of timber (Paper III). At the regional level, the substitution impacts increased by up to 29% over the study period, when maintaining lower stocking with earlier final felling, compared to the baseline. In this case, the contribution of a carbon stock of sawn wood to the climate impacts was higher than for pulp/paper products, regardless of the timing of final felling (Paper III). Sawn wood products retained carbon out of the atmosphere for longer than pulp/paper products (Bowyer et al. 2010; Pingoud et al. 2010; Bergman et al. 2014), and the substitution impacts of wood products, along with increased carbon stocks, enhanced the climate impacts further, which is in line with previous studies (Jasinevičius et al. 2015; Nepal et al. 2016; Gustavsson et al. 2017; Xu et al. 2017).

When logging residues, coarse roots, and stumps as energy biomass, together with timber, were harvested in final fellings, the climate impacts increased the most, compared to the harvesting of only timber (Table 3) (Papers I, III). This was because the intensified harvest of logging residues and roots decreased CO_2 emissions, due to the avoidance of their onsite decay and their use in offsetting fossil fuels, which has been found to increase their climate impact in the long term, instead of them being left in the forest (e.g., Sathre and Gustavsson 2011, 2012; Repo et al. 2012, 2015a; Gustavsson et al. 2015). Using energy biomass initially produced higher emissions compared to that of fossil fuels, however, in the long term, climate benefits were gained due to carbon sequestration and the use of wood products (Paper I). Maintaining 20% lower stocking in thinning is an exception (Paper I), since it decreased carbon sequestration in forests, due to increased thinnings, that could not produce the climate benefits of substitution in the long term.

Using high displacement factors and high timber use efficiency increased cooling climate impacts under higher stocking in all of the initial age structures of forests (Table 3) (Paper II). In addition, the effects of forest management on climate impacts were small, compared to those of the displacement factors. The CCME per cubic meter of forest biomass was higher for about 2–46 years when maintaining higher stocking in forests, after which, maintaining lower stocking with high displacement factors, or timber use efficiency, increased the CCME, depending on the initial age structure of the forests (Paper II). This was because the use of high displacement factors, or timber use efficiency, compensated for the loss of carbon sequestration in lower stocking, but they lowered the climate benefits of carbon sequestration by using higher stocking. Use of high displacement factors also favored earlier final fellings and the use of energy biomass in substitution (Paper III). Therefore, in assessing the climate impacts of forest-based biosystems in the long term, the short-term development of sinks, integrated with substitution impacts and stocks of wood products, should be considered (Eriksson et al. 2007; Lippke et al. 2011; Alam et al. 2017; Smyth et al. 2017a, 2017b).

The magnitude of the default values for the displacement factors used in this study was in line with those of previous studies (e.g., Sathre and O'Connor 2010; Knauf et al. 2015; Geng et al. 2017), but the development of wood-based products, and their uses in substituting for fossil-based materials in the textile, furniture, and construction sectors, may affect the magnitude of the displacement factors currently used (Werner et al. 2015; Rüter et al. 2016; Suter et al. 2017). For example, the use of wood-fibre-based viscose as a substitute for oil-derived fibers in textiles is expected to increase the factors up to 2.2 tC tC^{-1} (Rüter et al. 2016). In the case of sawn wood as a substitute for concrete and aluminium, the factors have been found to be 2.74 and 5.1 tC tC^{-1}, respectively (Cintas et al. 2016; Suter et al. 2017). On the other hand, the development of fossil systems, and the use of different functional units, will affect the displacement factors of wood products (Sathre and O'Connor 2010; Ter-Mikaelian et al. 2015a; Smyth et al. 2017a). In addition, the assumption that all wood products substitute fossil-based materials, which may not be the case all the time, may exaggerate the substitution impacts (Soimakallio et al. 2016). In this work, the same displacement factors were used across the scenarios to study the effects of management and harvest intensity on climate impacts of biomass production and utilization. Therefore, the use of different displacement factors affected only the level of climate impacts and did not change the conclusion on the preference of forest management.

The climate impacts of forest biomass production and utilization were also dependent on the reference forest management used in the fossil system (Paper I). When the fossil system was considered only with the emission factors for fossil materials and fuels, the biosystem generated the greatest climate benefits, and over long rotations. When unthinned was selected as a reference, climate benefits for the biosystem were, in general, lower than in the case of the baseline as a reference, and the greatest climate benefits were gained for the 60-year rotation. When the baseline management was used as a reference, long rotations (80–100 years) generated the greatest climate impacts (Paper I). Variations in climate benefits in the biosystem, in comparison to the fossil system, could be explained by the fact that an increased number of thinnings (up to four) over long rotations resulted in a higher loss of carbon stocks in the forests than in the short rotations (60 years), where the number of thinnings was up to two. In addition, higher mortality occurred in the unthinned stand over longer time periods, which benefitted the biosystem in the net climate impact calculation. In the long term, unthinned stands may be vulnerable to abiotic and biotic risks, and natural mortality (Blennow et al. 2010; Lundmark et al. 2014), which also affects the climate impacts.

In Finland, the total emissions, excluding the LULUCF sector, in 2015 were about 56 million Mg CO_2 eqv (Official Statistics of Finland 2017). Conversely, the LULUCF sector acted as a carbon sink (26 million Mg CO_2 eqv), albeit harvested wood products were excluded. According to Paper III, by including harvested wood products, forests in southern Finland would have the potential to achieve climate impacts (5.1–5.8 Mg CO_2 ha^{-1} a^{-1}, i.e., 45–51 million Mg CO_2 a^{-1} scaling up to the total study area), on average, over the next 40 years, by maintaining higher stocking in thinnings and intensifying the biomass harvest in final fellings. Maintaining higher stocking produced the greatest climate change mitigation impact per harvested timber (1.0, 1.1, and 0.9 Mg CO_2 m^{-3}) in the normal (mostly middle-aged), right-skewed (mostly young), and left-skewed (mostly mature) forest structures, respectively (Paper II) (data not shown in Figures). This is somewhat higher than values documented in other studies (0.47–0.72 Mg CO_2 m^{-3}, Werner et al. 2010; Lundmark et al. 2014; Braun et al. 2016), in which the harvesting of logging residues and/or stumps was included, although this was not included in Paper II. The results of the climate impacts in Paper III are also comparable to the ranges of 2.3 to 8.1 Mg CO_2 ha^{-1} a^{-1}, depending on management, in the national-level studies of Sweden and Switzerland (Werner et al. 2010; Lundmark et al. 2014).

4.4 Conclusions

This study found that the greatest climate impacts of forest biomass production and utilization under Finnish boreal conditions were gained by maintaining up to 20% higher stocking in thinnings, and using nitrogen fertilization and 80–100-year rotations. These measures increased carbon sequestration, along with timber (especially production of sawlogs) and energy biomass yields, that could be used in substituting for fossil-based materials and energy. There was a tradeoff between management scenarios, however, between the greatest climate impacts and the economic profitability of biomass production. The greatest climate impacts were found when intensified biomass harvesting in final felling (timber, together with logging residues, coarse roots, and stumps) was performed, and the prominent regions for increasing climate impacts over the next 40-year period were the southern and eastern sub-regions of Finland. It was also found that the effects of substitution and timber use efficiency on climate impacts were higher than those of thinning regimes. Furthermore, the climate impacts were also found to be sensitive to the initial conditions set for the analyses, which affected the timing of the climate impacts, and the preference for forest management in climate change mitigation. This indicates that management measures, together with the initial conditions of forests, should be considered when evaluating efficient options for increasing climate impacts in forests, and in substituting fossil-based materials and energy with forest biomass.

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