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Aerosol emissions of forest biomass use and their climate impacts – a life cycle assessment perspective

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Academic dissertation
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ABSTRACT

The replacement of fossil fuels and fossil fuel intensive materials with forest-based products, energy biomass and timber processing residues will influence the global climate through changes in both greenhouse gas (GHG) and aerosol emissions to the atmosphere. To date, aerosol emissions from forest biomass use have received little study, and a deeper understanding would enhance the climate impact and sustainability assessments of the forest bioeconomy. In this thesis, anthropogenic aerosol emissions from forest biomass use and their climate impacts were studied. Thus, particulate matter (PM) emissions (including total suspended particles (TSP), respirable particulate matter (PM10), fine particulate matter (PM2.5) and black carbon (BC)) and gaseous emissions (including nitrogen oxides (NO_x), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOCs)) were calculated for forest-based products and energy biomass and for their non-forest-based counterparts, with the different production stages within the life cycle taken into consideration. Substitution effects of forest biomass were assessed by the calculation of displacement factors (DFs) for aerosol emissions when forest biomass replaced non-forest-based materials and energy. Radiative forcings of BC, organic carbon (OC) and SO_2 emissions were evaluated through increased forest biomass use scenarios in Finland. According to the results, emissions from sawlogs and pulpwood were less than from energy biomass, especially when the biomass was combusted in small-scale appliances. The DFs indicated that aerosol emissions from forest-based products and energy biomass are in many cases greater than those from non-forest-based counterparts. However, some substitution benefits were also found, most notably for wood-based textiles. The way that forest biomass was used notably affected aerosol emissions and their climate impacts, underscoring the importance of assessing aerosol emissions alongside GHGs to fully understand the climatic and environmental consequences of forestry.

Keywords: forest management, renewable resources, climate change, radiative forcing, substitution effects, short-lived climate forcers.

TIIVISTELMÄ

Fossiilisten polttoaineiden ja fossiiliperäisten materiaalien korvaaminen metsäpohjaisilla tuotteilla ja energiabiomassalla sekä ainespuun tuotannon sivutuotteilla vaikuttaa ilmastoon muuttaen sekä ilmakehään vapautuvia kasvihuonekaasu- (GHG) että aerosolipäästöjä. Metsäbiomassan käytön aerosolipäästöjä on tähän mennessä tutkittu niukasti, ja syvempi ymmärrys kehittäisi metsäbiotalouden ilmastovaikutus- ja kestävyysarviointeja. Tässä väitöskirjassa tutkittiin ihmistoiminnan aiheuttamia metsäbiomassan käytön aerosolipäästöjä ja niiden ilmastovaikutuksia. Metsäpohjaisille tuotteille ja energiabiomassalle sekä niiden ei-metsäpohjaisille vaihtoehdoille arvioitiin elinkaaren aikana eri tuotantovaiheissa syntyvät hiukkaspäästöt (mukaan lukien kokonaisleijuma (TSP), hengittyvät hiukkaset (PM10), pienhiukkaset (PM2.5) ja musta hiili (BC)) ja kaasumaiset päästöt (mukaan lukien typen oksidit (NO_x), rikkidioksidi (SO_2) ja ei-metaaniset haihtuvat orgaaniset yhdisteet (NMVOCs)). Metsäbiomassan käytön korvausvaikutukset arvioitiin laskemalla korvauskertoimet (DF) aerosolipäästöille, kun metsäbiomassalla korvataan ei-metsäpohjaisia materiaaleja ja energiaa. BC-, orgaanisen hiilen (OC) ja SO_2-päästöjen aiheuttamat säteilypakotteet laskettiin metsäbiomassan lisäkäytön skenaarioille Suomessa. Tulosten mukaan sahatavaran ja kuitupuun aerosolipäästöt olivat matalat verrattuna energiabiomassaan, erityisesti jos energiabiomassa käytettiin pienpoltossa. Korvauskertoimet osoittivat, että aerosolipäästöt metsäpohjaisista materiaaleista ja energiabiomassasta ovat monissa tapauksissa suuremmat kuin ei-metsäpohjaisilla vastineilla. Joitakin korvaushyötyjä kuitenkin havaittiin, selvimmin puupohjaisten tekstiilien osalta. Metsäbiomassan käyttötapa vaikutti huomattavasti aerosolipäästöihin ja niiden ilmastovaikutuksiin korostaen tärkeyttä arvioida aerosolipäästöt kasvihuonekaasujen rinnalla metsäsektorin ilmasto- ja ympäristövaikutusten ymmärtämiseksi.

Avainsanat: metsänhoito, uusiutuvat luonnonvarat, ilmastonmuutos, säteilypakote, korvausvaikutukset, lyhytikäiset ilmastoon vaikuttavat yhdisteet.

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I am deeply thankful to my parents, siblings, as well as other relatives and acquaintances for their support and encouragement. All the interest shown in my thesis work and the related conversations have given me more motivation to continue enthusiastically pursuing science. It has been a joy to see that my research topic has sparked curiosity, even though it may be unfamiliar. The kind and thoughtful questions have reminded me that research can be interesting even outside the academic world – and sometimes that is when it becomes the most fun.

A thousand thanks also to all my old and new friends, who have been part of this journey, for the great times we have shared together during leisure time. It has always been a pleasure to catch up with you, and to relax together during whatever activities we have shared. These moments have been invaluable and made all this such a pleasure. I could say that one of the most important lessons during my thesis has been that good friends and humour are the best help to turn challenges into fun experiences and that is something I know I will always remember, especially because the exciting challenges do not end here.

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Joensuu, 8th October 2025
Aapo

LIST OF ORIGINAL ARTICLES

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I–IV.

I Vento E, Hartikainen A, Tikka A, Lamberg O, Sippula O, Kilpeläinen A (2024) Integrating aerosol emissions of forest biomass into a life cycle assessment of forest-based production. Biomass and Bioenergy 183, article id 107156. https://doi.org/10.1016/j.biombioe.2024.107156

II Tikka A, Hartikainen A, Sippula O, Kilpeläinen A (2024) Displacement factors for aerosol emissions from alternative forest biomass use. Global Change Biology Bioenergy 16(12), article id e70008. https://doi.org/10.1111/gcbb.70008

III Tikka A, Irfan M, Mielonen T, Kokkola H, Hartikainen A, Sippula O, Kilpeläinen A (2025) Radiative forcing of aerosol emissions under alternative wood use scenarios in Finland. Global Change Biology Bioenergy 17(9), article id e70041. https://doi.org/10.1111/gcbb.70041

* See corrigendum to Article I at the end of this summary

AUTHOR CONTRIBUTION

The publications included in this dissertation are original and peer-reviewed research that were planned in collaboration with the supervisors and co-authors. The author carried out the acquisition, analysis, and interpretation of data in Article **II** and of emission data in Article **III**, as well as a substantial part of data analysis in Article **I**. All numerical computations in Article **II** were performed by the author, who also contributed substantially to the computations in Articles **I** and **III**. The author was responsible for the visualisation of the results in Articles **I** and **II** and contributed to the visualisation in Article **III**. The initial drafts of Articles **II** and **III** were written by the author as the main author. The author also played a major role in drafting and editing Article **I** as a co-author, coordinated the review processes for Articles **II** and **III**, and contributed significantly to the revisions in Article **I**. The final versions of the articles were improved through the contributions of all co-authors.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ACI	Aerosol–cloud interactions
ARI	Aerosol–radiation interactions
BC	Black carbon
BVOC	Biogenic volatile organic compound
C	Celsius
CCB	Corrugated cardboard
CCN	Cloud condensation nuclei
CH_4	Methane
CO_2	Carbon dioxide
DF	Displacement factor
EE	Embodied energy
ERF	Effective radiative forcing
EU	European union
g	Gram
GHG	Greenhouse gas
G	Giga (10^9)
ha	Hectare (10^4 m^2)
HDPE	High-density polyethylene
hPa	Hectopascal
HWP	Harvested wood product
IRF	Instantaneous radiative forcing
k	Kilo (10^3)
LCA	Life cycle assessment
LSB	Medium- to large-scale burning
m	Metre
M	Mega (10^6)
J	Joule
MT	*Myrtillus* type (mesic forest site type)
MWth	Megawatt thermal
NMVOC	Non-methane volatile organic compound
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
OC	Organic carbon
PM	Particulate matter
PM2.5	Particulate matter with diameter less than 2.5 μm
PM10	Particulate matter with diameter less than 10 μm
RF	Radiative forcing
SLCF	Short-lived climate forcer
SO_2	Sulphur dioxide
SOA	Secondary organic aerosol
SSB	Small-scale burning
T	Tera (10^{12})
t	Tonne
TSP	Total suspended particles
VOC	Volatile organic compound
W	Watt

1. INTRODUCTION

1.1 Background to the thesis

Climate change, along with biodiversity loss, may have become the toughest challenge for humanity and the biosphere. The reasons for current global warming are complicated but are primarily due to anthropogenic activities (Ring et al. 2012; Al-Ghussain 2019). Forests can contribute to climate change mitigation through carbon sequestration and by storing the carbon in both forests and forest-based products. For climate change mitigation purposes, the ongoing energy transition has increased the global industrial demand for forest biomass, as many fossil fuel intensive materials and fossil fuels can be replaced by forest-based products and energy biomass, and residual biomass from timber processing. This will lead to changes in both greenhouse gas (GHG) and aerosol emissions to the atmosphere, which will have a substantial effect on the global climate (IPCC 2023). As a result of forest biomass use, concerns related to the maintenance of forest carbon sinks (Lin and Ge 2020; Peng et al. 2023; Roebroek et al. 2023) and the ecological sustainability of forestry (e.g. Daskalova et al. 2020; Betts et al. 2022; Ma et al. 2023) have also been raised.

Aerosol emissions consist of primary particulate matter (PM) and precursor gases for secondary aerosols and influence the climate through their impact on radiative forcing (RF), which quantifies the changes in the Earth's energy balance, primarily through aerosol–cloud interactions (ACI) and aerosol–radiation interactions (ARI) (Szopa et al. 2021). The climate effects of aerosols mainly occur locally in the regions where they are emitted or in adjacent areas to which they are transported (Kuylenstierna et al. 2011) because of their short residence time (typically a few days) in the atmosphere (Kuylenstierna et al. 2011). Collectively, aerosols cool the climate through light scattering, by increasing cloud droplet numbers, through enhancing brightness, reducing rainfall, extending cloud lifetimes and, in some cases, expanding the cloud cover (Spracklen et al. 2008; Rosenfeld et al. 2014; IPCC 2021). From 1850–1900 to 2010–2019, the global cooling effect caused by aerosols has ranged from 0.0 to 0.8°C (Szopa et al. 2021). Ambient air quality is also influenced by aerosol emissions, and its deterioration due to air pollution have caused serious health impacts globally and has led to over 4 million premature deaths every year (Kennedy 2007; Lepeule et al. 2012; Shiraiwa et al. 2017; Murray et al. 2020; Arfin et al. 2023). Climate change may even exacerbate those impacts (Burney et al. 2024). In particular, PM that includes fine particles (particles with diameters <2.5 μm, PM2.5) and respirable particulate matter (particles with diameters <10 μm, PM10) are well known for their adverse health effects (Lepeule et al. 2012; Alemayehu et al. 2020; Villarroel et al. 2024).

Globally, the industry sectors that produce the most PM2.5 emissions are cement, iron and steel production, which together represent about 75% of global industrial PM2.5 emissions (Klimont et al. 2017). Black carbon (BC) is an optically defined PM component that is specifically released from forest fires, biomass combustion in small-scale appliances, traffic and flaring in oil fields (Bond et al. 2013; Denier van der Gon et al. 2015; Butt et al. 2016; Huang and Fu 2016). BC mainly consists of elemental carbon and exhibits strong light absorption across the visible light spectrum (Petzold et al. 2013). Since 1850–1900, the effective radiative forcing (ERF), which includes any consequent adjustments within the climate system but excludes the impact of surface temperature changes, of BC has been positive (0.11 Wm^{-2} with an absolute error of ±0.31 Wm^{-2}) (Szopa et al. 2021). Particulate

organic carbon (OC) is mostly derived from biological sources or combustion processes, and OC from non-biological wood use (in industrial or human-driven processes) is estimated to have produced an ERF of −0.21 (±0.23) Wm^{-2} (Szopa et al. 2021).

Precursor gases that participate in the formation of the secondary aerosols released from combustion and industrial processes (e.g. textile production (Guo et al. 2022)), include sulphur dioxide (SO_2), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs). Emissions of precursor gases can either cool or warm the climate (IPCC 2021). With a RF of −0.94 (±0.69) Wm^{-2} (Szopa et al. 2021), SO_2, is naturally released from volcanic activity and can cool the climate and contribute to drought and acid rain. However, at excessive levels, SO_2 can cause warming by overwhelming the oxidising capacity of the atmosphere (Ward 2009). In turn, anthropogenic NO_x emissions (traffic is a major source) (Cox 1999) have caused a RF of −0.27 (±0.28) Wm^{-2} (Szopa et al. 2021). Volatile organic compounds (VOCs) also contribute to aerosol formation and influence the formation of ozone in the atmosphere, a process that is also strongly affected by NO_x. In general, the in-cloud chemistry of organic gases that have originated from wood burning may efficiently produce aerosols that affect the climate and lead to deterioration in air quality (Wang et al. 2024b).

Globally, aerosols are released in large quantities both by anthropogenic and natural sources (Streets et al. 2003; Wu et al. 2020; European Commission 2022). For instance, global anthropogenic emissions in 2022 were estimated at 4.7 Mt BC, 11.6 Mt OC, 93.2 Mt SO_2 and 138.1 Gt NMVOCs (European Commission 2022), whereas global emissions of biogenic volatile organic compounds (BVOCs), specifically VOCs that have originated from compounds formed by metabolic processes in plants (Kulmala et al. 2001), are estimated at 835.4 Tg $year^{-1}$ (Wang et al. 2024a). The largest quantities of anthropogenic aerosol emissions are released in Southern and Eastern Asia, North America (especially the eastern side), Europe and some developing countries (European Commission 2022). The boreal region also produces notable amounts of aerosol emissions (Tunved et al. 2006; Spracklen et al. 2008).

Biogenic forest-based aerosols are known to significantly affect the climate (Yli-Juuti et al. 2021; Petäjä et al. 2022). In climate change mitigation, however, anthropogenic emissions play a central role due to their distinct composition and spatial distribution compared to natural sources (Shindell et al. 2012; Szopa et al. 2021), and they are also easier to reduce compared to biogenic emissions, which are not typically classified as air pollutants. Between anthropogenic and biogenic aerosols (Kulmala et al. 2001) are aerosols that have originated from natural and human-ignited forest fires, which release aerosols not only from combustion of the vegetation layer but also from the soil (Chen et al. 2023). These aerosols impact RF both directly and indirectly by altering the glacier albedo, as light-absorbing particles are deposited on the glacier and snow (Williamson and Menounos 2021). Small-scale burning (SSB), for instance, can result in similar effects (Cuesta-Mosquera et al. 2024). To date, forest research on aerosol emissions has mainly considered BVOCs (Lindfors and Laurila 2000; Aaltonen et al. 2011; Kulmala et al. 2013; Gray et al. 2014), whereas the holistic aerosol emissions from forest biomass use have received much less attention (cf. Savolahti et al. 2016; Wolf et al. 2016; Arvesen et al. 2018; Tissari et al. 2019). Recent research has revealed that the origin of biomass-based aerosols is an important factor in determining the impact of emissions, as the composition of the emissions can vary considerably depending on factors, such as the combusted wood species (Rinta-Kiikka et al. 2024), the regions where the fires occur and the types of fires themselves (Holmberg and Gustavsson 2007; Dobracki et al. 2023; Marsavin et al. 2023; May et al. 2023). As a consequence, aerosol-related RFs can vary significantly between seasons (Tariq et al. 2023; Gramlich et al. 2024).

In Europe, especially Nordic countries, where industrial use of wood is extensive, residual biomass from forest-based production has been used effectively for energy generation (Hassan et al. 2019). In Finland, for instance, 56% of the harvested biomass is combusted within a few years after harvest (Natural Resources Institute Finland 2021). Thus, an increase in the production of sawn wood or pulp products will also increase the use of forest-based energy. This leads to the following consequences: (1) fossil fuel-based GHG emissions are decreased; (2) a notable amount of the carbon sequestrated in the forests is rapidly released into the atmosphere as carbon dioxide (CO_2); and (3) the quantities and qualities of aerosol emissions from the energy and industrial sectors are significantly changed. Even though the role of forests in the mitigation of CO_2 emissions has been widely studied, there is currently little information on the changes in aerosol emissions caused by the alternative use of forest biomass (Wolf et al. 2016; Andreae 2019; Aamaas and Grimsby 2024; Tripathi et al. 2024). Current forest biomass use, especially for combustion, rapidly releases carbon (Ter-Mikaelian et al. 2015) and contributes to ambient PM levels both by emitting primary particles directly from the source and by emitting secondary aerosol precursor gases into the atmosphere (Finnish Environment Institute 2021). Since forest biomass can be utilised in several different ways (e.g. in energy production, construction, the paper and cardboard industry, the textile industry or in the transport sector as biofuels), the way it is used influences the amount and type of aerosols released to the atmosphere. The various manufacturing processes associated with forest-based products and the use of biomass for energy production requires that aerosol emissions from forest-based production systems are tracked for the full life cycle. This enables the climate impacts of aerosol emissions in the forestry sector to be minimised by carefully considering how the forest biomass is used.

Substitution effects of forest biomass can be expressed by displacement factors (DFs), which describe the amount of reduced or increased emissions per unit of wood use when fossil counterparts are replaced by a functionally equivalent product or amount of energy from wood (Sathre and O'Connor 2010). Thus, DFs are influenced by both the emissions of forest-based and non-forest-based alternatives. For instance, the production of steel and concrete is known for its high energy requirements (Hasanbeigi et al. 2014), and likely results in substantial GHG and aerosol emissions. The aerosol emissions from the oil industry (Huang and Fu 2016) significantly influence life-cycle emissions from plastic and synthetic textile production. In plastic production, the production stage causes the most carbon emissions, mainly due to the use of coal for electricity and the need for heat in resin production and the manufacture of the plastic products (Cabernard et al. 2022). Until now, DF studies that have focused on GHG emissions (i.e. CO_2, methane (CH_4) and nitrogen dioxide (NO_2)) have indicated that forest-based products often have less emissions compared to their fossil-based counterparts; therefore, industrial carbon emissions could be decreased by favouring the use of forest biomass (e.g. Sathre and O'Connor 2010; Alam et al. 2017; Nabuurs et al. 2017; Smyth et al. 2017, 2020; Leskinen et al. 2018; Hudiburg et al. 2019; Seppälä et al. 2019; Freer-Smith et al. 2023; Khan et al. 2024).

In recent decades, the growing understanding of the relationship between air quality and health, as well as the environmental effects of aerosols (Roudier et al. 2015; Wilnhammer et al. 2017) has led to the evolving regulation of aerosol emissions. Emissions from energy production can be significantly reduced by clean technology innovations in combustion systems (Wilnhammer et al. 2017), and substantial variations in aerosol emissions have been reported across different combustion appliances (Savolahti et al. 2016). The aerosol substitution effects of forest-based materials and energy biomass should be carefully considered, especially if the aerosol emissions produced by forest biomass use are found to

be significant. In Finland, aerosol emission data related to the industrial use of various fuels are regularly collected (e.g. Finnish Environment Institute 2021).

While the substitution effects of forest biomass may also be affected by the differences in the properties of the aerosols emitted from the combustion of forest biomass and fossil fuels (Penner et al. 2003; Reimann and Lewis 2007), lack of knowledge of aerosol emissions in climate impact studies may have led to bias in the current understanding of the comprehensive environmental and ecological consequences of forest biomass use. A deeper understanding of aerosol emissions improves the assessments of climate impacts and the sustainability of the forest bioeconomy. Thus, adequate consideration of aerosol emissions will be a notable step towards more comprehensive evaluations.

1.2 Aims and hypotheses of the thesis

The objective of this thesis was to quantify aerosol emissions from forest biomass use and estimate their climate impacts from a life cycle perspective. Ecosystem model simulations and life cycle assessment (LCA) were integrated to quantify aerosol emissions from alternative uses of forest biomass. Substitution effects of forest biomass use were quantified by applying DF calculations to the most important aerosol emission components. Climate impacts of anthropogenic forest-based aerosol emissions were estimated in terms of RFs through alternative scenarios of increased forest biomass use in Finland.

The specific aims of the publications were:

I) To quantify aerosol emissions from the use of forest biomass, fossil-based materials and fossil fuels by utilising the LCA tool for forest-based production.
II) To quantify the substitution effects of aerosol emissions from the alternative use of forest biomass.
III) To estimate RF of alternative scenarios of increased forest biomass use in Finland.

The hypotheses were:

I) Aerosol emissions from forest biomass use significantly differ from those of fossil-based materials and energy.
II) Consideration of aerosol emissions will notably alter our understanding of the substitution effects of forest biomass use.
III) Increased use of forest biomass will have a significant impact on RF of aerosol emissions, depending on how the forest biomass is used.

2. MATERIALS AND METHODS

2.1 System boundaries of the study (Articles I, II and III)

Aerosol emissions from forest biomass were calculated over the full life cycle, encompassing the transportation, production and use phases. The end-of-life phase was excluded due to a lack of data, significant differences in emissions between different end-use options of materials (Carpenter et al. 2013; Backes et al. 2022), and the differences in the length of the life cycle of comparable products (Bauer 2012; Struhala and Sochorová 2015). In the calculations, non-forest-based materials and energy were used as counterparts to forest-based materials and energy, and aerosol emissions followed the same system boundaries as forest-based materials and energy. Biogenic emissions were excluded from the study because of their considerable complexity, and the initial production phase (raw material extraction) was also excluded in the case of non-forest-based counterparts.

Aerosol emissions were calculated for pulp wood, sawn wood and energy biomass. The forest-based products considered in the studies were cardboard, viscose-based textiles, sawn wood in construction and energy combusted in small-scale appliances (SSB) or in medium- to large-scale burning scale boilers (LSB, plant power > 1 MWth). In SSB, energy biomass was combusted for residential heating, for example, in wood-fired boilers and stoves, without any emission after-treatment technologies that would decrease aerosol emissions. In LSB, energy biomass combustion is usually based on grate combustion, fluidised bed combustion or pulverised fuel combustion technologies. The non-forest-based counterpart of cardboard was HDPE plastic, and those of viscose-based textiles were flax, cotton, polypropylene, polyester, acrylic and nylon. Concrete, steel and bricks were considered as non-forest counterparts for the use of sawn wood in construction. For energy biomass, the counterparts were coal, heavy fuel oil, light fuel oil, milled peat, sod peat, diesel oil, natural gas and gasoil. The most important aerosol emission components were considered, namely, directly emitted PM (i.e. TSP, PM10, PM2.5 and BC) and the gaseous emissions that participate in the formation of secondary aerosols in the atmosphere (i.e. NO_x, SO_2 and NMVOCs).

Emissions from cardboard production were calculated to include those from transport of pulp wood for 70 km (i.e. the average transport distance) and the combustion of the by-products of pulp production, taking into consideration the amount of fossil fuels used in the pulping processes (Roudier et al. 2015). Emissions from sawn wood were calculated to include those from the transport of the sawn timber for 70 km, combustion of sawmilling by-products (e.g. bark and saw dust) and the electricity required to produce 1 dry tonne of sawn wood in the sawmills (Sahateollisuus 2020). In the case of wood-based viscose, emissions were calculated to include those from the combustion of the by-products of chemical pulp production and the required energy for viscose fabric production (Barber and Pellow 2006). Emissions from energy included aerosol emissions from the combustion of the forest biomass and their fossil-based counterparts and peat, but emissions from extraction and transportation were excluded. The system boundaries used in all studies are described in Figure 2 in Article I and in Figure 1 in Article II.

2.2 Data used in the study and functional units (Articles I and II)

The emission factors for the various fuels used in the aerosol emissions calculation were collected from the existing literature (Finnish Environment Institute 2021). Embodied energies (EEs) of the materials were used to calculate the emissions for HDPE plastic and non-forest-based construction and textile materials (Barber and Pellow 2006; Hammond et al. 2011; Hildebrand 2014). Particulate emissions from flaring in oil production, based on Conrad and Johnson (2017) and Väätäinen (2019), were considered when the DF for HDPE plastic were calculated. Energy profiles for the production processes of HDPE plastic and construction materials (Metallinjalostajat ry 2014; Finnsementti 2018; European Union 2019; Wienerberger 2019; Benavides et al. 2020) were made with the assumption that electricity production was the same as the fuel mix used in Finland (Finnish Energy 2023). Global average fuel mixes were used to calculate the emissions for electricity and heat in textile production (World Business Council for Sustainable Development 2018; Ritchie et al. 2022).

Emissions from energy production were calculated for the quantity of forest biomass or fossil fuel required to produce one unit of energy (kg TJ^{-1}) based on the unit emissions of energy sources in Finland (Finnish Environment Institute 2021). Emissions of LSB were based on the emissions from the combustion of forest biomass in Finland (Finnish Environment Institute 2021) and considered the realistic use of different tree parts in various applications based on data from Natural Resources Institute Finland (2022) (Article I). For SSB, emissions and the proportion of the different small-scale applications in Finnish residential wood combustion were estimated based on data from 2020 (Savolahti et al. 2019) (Article I), emissions from sauna stoves (Tissari et al. 2019) and the calorific values of different tree parts (Alakangas et al. 2016).

For forest-based materials, aerosol emissions were calculated for the mass unit of timber required to produce one tonne of product (g t^{-1}). Emissions of sawn wood use were also calculated for one square metre of wall (g m^{-2}) and for one square metre slab with an average weight of one bearing column (g m^{-2}), which represents the typical load-bearing structure in office buildings (Hildebrand 2014). Alternative functional units were used to illustrate the different cases in substitution effect assessment and the variability in substitution effects of forest-based materials. The quantity of forest-based materials was determined by the yield of sawn wood or pulp in the forest industry (Hiltunen et al. 2021; Kilpeläinen et al. 2011) (Table A.1 in Article I). The by-products of sawn wood and pulp production complied the side streams from the Finnish forest industry in 2016 (Hassan et al. 2019). The yield of viscose pulp (36.4% from timber dry mass) was determined using information from Canopy (2020). Emissions associated with electricity use in sawmills and the pulp industry followed the average fuel mixes in electricity production in Finland in 2022 (Finnish Energy 2023).

2.3 Models and methods used in the study (Articles I, II and III)

In Article I, the gap-type ecosystem model SIMA (Kellomäki et al. 1992, 2008) was used to calculate the amount of timber (pulpwood and sawlogs) and energy biomass (delimbed stems from first thinning and/or logging residues from final felling) harvests (Figure 1 in Article I). The simulations were conducted on 10,000 m^2 (equal to 1 ha) of forest land in mid-boreal conditions (central Finland, Joensuu region: 62°39′N, 29°37′E, temperature sum 1150–1200 degree days). The growth and development of a Norway spruce (*Picea abies*) stand with medium fertility site type (MT) was simulated for production of forest biomass. Simulations

were done over an 80-year period following the recommendations provided for practical forestry in Finland (Äijälä et al. 2014). The LCA tool (Kilpeläinen et al. 2011; Hiltunen et al. 2021) divided timber into harvested wood products (HWPs) and their processing wastes that were combusted for energy.

The existing aerosol emission data from literature were integrated into the LCA tool to estimate the aerosol emissions released from the use of HWPs and energy biomass (Figure 1 in Article I). Aerosol emissions from HWP use were compared to those of fossil-based materials, i.e. concrete, steel, bricks and HDPE plastic. Aerosol emissions from forest-based energy use were compared to the energy use of coal, oil, natural gas and peat. The aerosol emissions that were calculated for forest management regimes are explained in detail in Table 1 in Article I.

In Article II, the substitution effects of forest biomass were described by calculating DFs for TSP, PM10, PM2.5, BC, SO_2, NO_x and NMVOC emissions. The DFs for forest biomass indicates the amount of emissions avoided by using forest biomass instead of some other material per functionally equivalent product or energy (Schlamadinger and Marland 1996; Sathre and O'Connor 2010; Leskinen et al. 2018). The DFs for aerosol emissions were calculated as follows:

$$DF = \frac{Aerosol_{non\text{-}wood} - Aerosol_{wood\text{-}based}}{Unit\ of\ material\ or\ energy} \qquad (1)$$

where $Aerosol_{non\text{-}wood}$ and $Aerosol_{wood\text{-}based}$ are the aerosol emissions that result from the use of non-forest-based and forest-based alternatives expressed in mass units. *Unit of material or energy* is a mass unit (dry tonne, t) in the case of a forest-based material or an energy unit (TJ) in the case of material or energy, respectively. Positive DF values indicate a decrease in emissions from the use of forest-based material or energy and negative values indicate an increase in emissions.

In Article III, DFs were used to estimate RFs associated with alternative scenarios of increased forest biomass use in Finland with the aerosol–climate model ECHAM-HAMMOZ (echam6.3.0-ham2.3-moz1.0) (Schultz et al. 2018). This model combined the ECHAM6 general circulation model (Stevens et al. 2013) and the HAM aerosol module, which simulates aerosol lifecycle processes, such as formation, growth and removal (Tegen et al. 2019). Further, ECHAM-HAMMOZ was integrated with SALSA, an aerosol microphysical model that uses a sectional method to simulate aerosol dynamics across 10 distinct size bins, thereby providing a more precise representation of aerosol–atmosphere interactions. SALSA includes key aerosol species, such as sulphate, OC, BC, sea salt and mineral dust. Beyond aerosol microphysics, it also integrates ACI and radiation processes, which permits investigation into aerosol effects on the Earth's radiative balance and climate. The parameterisation of cloud droplet activation follows the method proposed by Abdul-Razzak and Ghan (2002). A detailed description of SALSA is provided in Kokkola et al. (2018).

In ECHAM-HAMMOZ, instantaneous radiative forcing due to ARI (IRF_{ARI}) was determined based on the methodologies described by Collins et al. (2006a) and Collins et al. (2006b), using the differences in radiative effects from ARI between the increased forest biomass use scenarios and the baseline scenario. In addition, ERF was calculated as the difference in net radiative flux at the top of the atmosphere between the baseline scenario and the alternative scenarios, which included contributions from ARI and ACI, as well as rapid adjustments to both forcings. The use of models in the studies and layout of the thesis are shown in Figure 1.

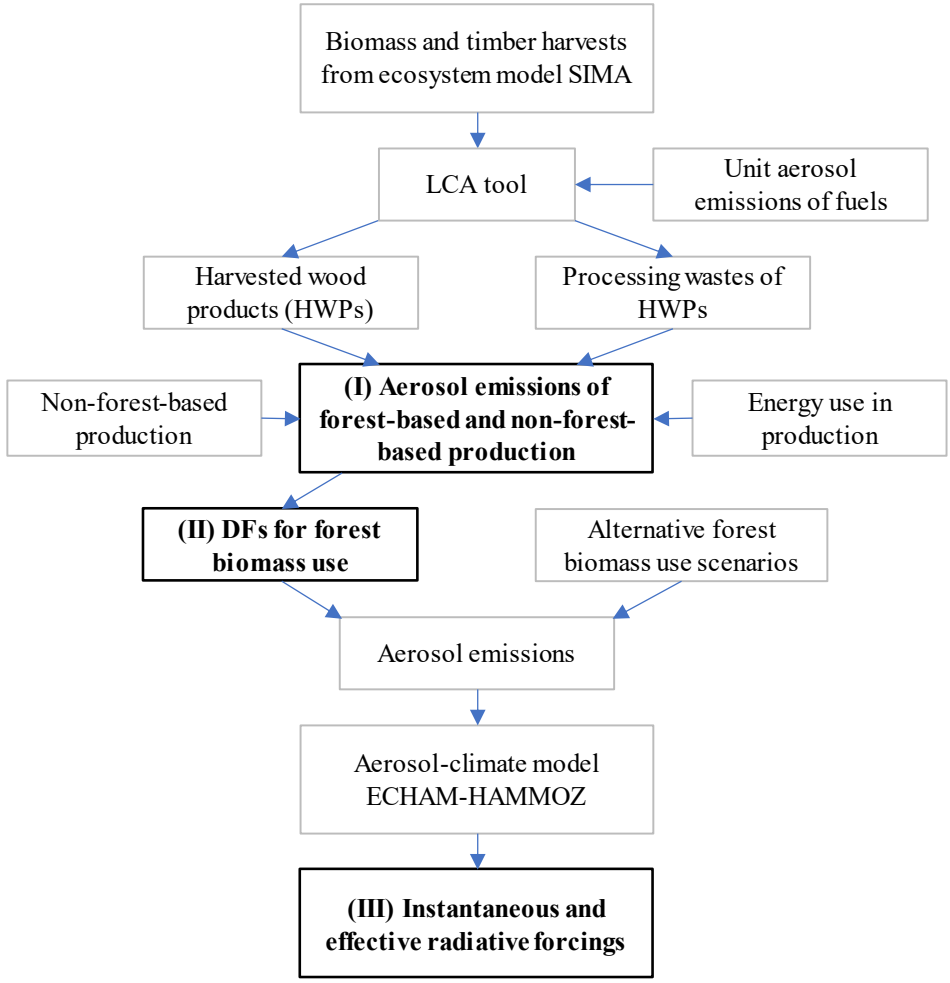

Figure 1. Layout of the thesis and the use of models in the studies I, II and III.

2.4 Calculation of displacement factors for forest biomass (Article II)

The DFs were calculated for the forest-based materials that replaced HDPE plastic and the most common construction and textile materials, and energy biomass that replaced general fossil fuels and peat. The DF calculations were based on existing data on aerosol emissions of fuels (Finnish Environment Institute 2021) which, for example in Finland, constitutes applicable and the best available database for aerosol DF calculations. The DFs for sawn wood were calculated against three general construction materials, i.e. concrete, steel and bricks. Since alternative construction elements require different amounts of materials, and there is also variability in the EE of materials, the DFs were determined per material tonne and per alternative functional unit as described in section 2.2. When alternative functional units were used, the nominator in Equation 1 considered the difference in material masses required to produce one functional unit either from forest-based or from non-forest-based

materials. The DFs for cardboard production were calculated for the replacement of HDPE plastic, and wood-based viscose was assumed to replace a selection of alternative textile materials, i.e. flax, cotton, wool, polypropylene, polyester, acrylic or nylon. The DFs for energy biomass were calculated against coal, oil, natural gas, coke, diesel oil, gasoil and peat, and separately for forest biomass combustion in SSB or LSB.

The effect of the most influential factors on the DFs of forest-based materials was examined with a sensitivity analysis with respect to the following aspects: 1) increased EE of HDPE; 2) discounting flaring emissions in oil production; 3) alternative fossil fuel mixes in the manufacturing processes associated with non-forest-based textiles and in electricity and heat production; 4) decreased or increased EE of steel (material tonne); 5) decreased or increased amounts of cement in concrete mixtures; and 6) decreased or increased unit emissions of the energy use of forest biomass. Greater EE values for HDPE were used as EE values of different plastic types can significantly vary, and in some cases can be twofold greater than HDPE plastics (Hammond et al. 2011). In the case of HDPE plastics, discounting PM emissions from flaring in oil production was included in the sensitivity analysis as oil flaring, while part of raw material extraction, constitutes a significant proportion of the total aerosol emissions of plastics (Conrad and Johnson 2017; Väätäinen 2019). For non-forest-based textiles, alternative fuel mixes represented the conditions in three large textile production countries or regions, i.e. Europe, China and USA (Guo et al. 2013; International Energy Association (IEA) 2013; Wang et al. 2017; U.S. Energy Information Administration 2021, 2023; Ritchie et al. 2022). Alternative EE values of steel and the amount of cement in concrete mixtures were used to demonstrate the differences between alternative steel and concrete qualities (Hammond et al. 2011). Alternative unit emissions from energy biomass were used to examine the differences in annual emissions or emissions in different countries.

2.5 Estimation of climate impacts (RF) of forest biomass use (Article III)

The IRF and ERF values associated with anthropogenic forest-based aerosols in Finland were assessed based on the aerosol emissions from alternative wood use scenarios in comparison to the baseline for 2030. The baseline scenario included the average roundwood (sawlogs, pulpwood and energy wood) harvest level in Finland in recent years (Natural Resources Institute Finland 2024a), i.e. 70 million m^3, of which 28 Mm^3 was harvested as sawlogs, 31.5 Mm^3 as pulpwood and 10.5 Mm^3 as energy biomass, based on the proportions of wood assortments reported by Natural Resources Institute Finland (2023a). The residual biomass from sawlog and pulpwood production were allocated to energy biomass combusted in LSB (Article I; Hassan et al. 2019). In the alternative scenarios, harvest level was increased to the maximum sustainable harvest level in Finland (80 Mm^3) (Natural Resources Institute Finland 2024b), and the increased harvest (10 million m^3) was allocated to be used in four different ways: (1) as sawn wood (scenario 80SW), (2) as pulp-based products (scenario 80PW), (3) as energy biomass used in SSB (scenario 80EB SSB), or (4) as energy used in LSB (scenario 80EB LSB). The local scale assessment was justified by the short residence time of aerosols in the atmosphere (Kuylenstierna et al. 2011). The scenarios used in Article III are explained in Table 1 in Article III.

The end-products from the increased harvests were assumed to be used entirely to replace non-forest-based counterparts. In the 80SW scenario, the increased harvest of sawlogs was used in construction to replace steel and concrete at a 1:1 ratio. In the 80PW scenario, half of the increased harvest of pulpwood was used to produce viscose-based textiles to replace

polyester and the other half was used to produce cardboard to replace and HDPE plastic. In the 80EB scenarios, the increased energy biomass harvest was assumed to replace the use of natural gas, peat, oil and coal by 25% either in SSB or LSB, depending on the scenario. The annual harvest level of forest biomass and the DFs for aerosol emissions from the alternative use of forest biomass (Article II) were used to estimate BC and SO_2 emissions in the industrial and energy sectors for the scenarios. Based on data from the ECLIPSE emission dataset (Klimont et al. 2017), OC emissions were assumed to follow BC emissions at a ratio of 0.8. Further, the amounts of the various aerosols were used to calculate the changes in the RFs due to increased use of forest biomass.

Five simulations were conducted, each represented an alternative forest biomass use scenario, with emissions adjusted according to harvest levels and the way that the forest biomass was used. To ensure realistic atmospheric conditions, the simulations were nudged using meteorological fields from 2000 to 2009. All simulations were run with T63 spectral truncation, which corresponded to a horizontal resolution of approximately 1.9° x 1.9°, and 47 vertical layers that extended up to 0.01 hPa (about 80 km altitude). Each spanned ten years, with the first three years used for spin-up.

3. RESULTS

3.1 Aerosol emissions from the use of forest biomass and non-forest-based counterparts over the life cycle (Article I)

In Article I, LCA of forest-based production under different management regimes (Table 1 and 3 in Article I) indicated that forest biomass use as sawlogs resulted in somewhat greater aerosol emissions than pulpwood, and that its use for energy production led to the greatest amount of aerosol emissions. The use of biomass for combustion in SSB caused notably greater aerosol emissions than combustion in LSB. In particular, BC and NMVOC emissions increased with energy biomass combustion in SSB. However, NO_x and SO_2 emissions were slightly greater in the LSB scenarios (Figures 3 and 4 in Article I).

The particulate and gaseous emissions associated with the processing of sawn wood were greater than those for concrete, steel and brick. The use of steel produced the second greatest particulate, NO_x and NMVOC emissions, while the use of bricks resulted in the third greatest NO_x emissions. However, the use of concrete caused the second greatest SO_2 emissions and greater TSP emissions than brick (Figure 5 in Article I). Pulpwood use also resulted in notable aerosol emissions, as both the particulate and gaseous emissions from the use of cardboard were greater than those from the use of HDPE plastic (Figure 5 in Article I).

The use of forest biomass for energy production caused greater TSP and NMVOC emissions than the use of fossil fuel counterparts and peat, especially in the SSB scenarios (Figure 5 in Article I). The use of peat caused the greatest NO_x emissions, and the use of coal caused the greatest SO_2 emissions. Furthermore, notable BC emissions were caused by forest biomass combustion in SSB. Compared to the baseline regime in which both coal and peat were used in energy production, their replacement with energy biomass and processing wastes from the forest industry in Finland resulted in increased aerosol emissions (Figure 6 in Article I).

3.2 Displacement factors for aerosol emissions from the use of forest biomass (Article II)

The calculations in Article II proved that DF calculations can be successfully applied for primary aerosol emissions and precursor gases for secondary aerosols. The DFs from the replacement of HDPE plastic with cardboard were positive for BC, NMVOC and SO_2 emissions, which implies reduced emissions, and were negative for NO_x, PM2.5 and PM10 (Table 4 in Article II). The use of sawn wood instead of concrete, steel or bricks largely increased all emissions components; positive DFs were only found for SO_2 emissions when concrete was replaced. Sawn wood DFs for BC were close to zero. When considering final products instead of material tonnes, the DFs were notably altered (Table 4 in Article II).

The DFs for the wood-based viscose used to replace non-wood textile materials were mostly negative for TSP, PM10 and PM2.5, which would suggest increased emissions. However, exceptions were found: for nylon, the DFs for these three particulate emission components were positive, and for acrylic, the DFs for TSP and PM10 were positive (Table 4 in Article II). The DFs for SO_2 emissions were positive for every textile material, which would imply a decrease in emissions due to the use of forest biomass. Also, DFs for NO_x and NMVOC were positive, except for the case where wood-based viscose replaced flax. Both

positive and negative DFs were found for BC, depending on the replaced textile material. The DFs for forest-based energy combusted in SSB were mainly negative. However, many of the DFs for NO_x and SO_2 emissions were positive, as was the DF for TSP emissions when forest-based energy replaced the energy use of sod peat (Table 5 in Article II). Biomass combustion in LSB did not have such negative substitution effects, as DFs mainly had elevated values, which would imply less emissions than those from SSB (Table 5 in Article II). The LSB–sod peat DFs were always positive, whereas the DFs for LSB in replacing natural gas, coke and gasoil were still negative for each emission component.

Sensitivity analysis showed that the alternative EE values of products may strongly influence DFs, especially in the case of cardboard when it replaced HDPE (Tables 6 and 8 in Article II). In addition, the energy profile of non-wood textiles was found to be a major factor that affected DFs (Table 7 in Article II). Other factors that significantly altered DFs included the exclusion of flaring-related PM emissions in HDPE production, and the amount of cement in the concrete mix (Tables 6 and 8 in Article II). The DFs were not exceptionally sensitive to changes in terms of the unit emissions of forest biomass, although the value could be slightly altered with a 10% increase or decrease (Table 9 in Article II).

3.3 Radiative forcing of aerosols from increased use of forest biomass (Article III)

The results presented in Article III showed the importance of aerosol DFs (Article II) through their integration into the RF calculations. The increased use of sawn wood (scenario 80SW) produced 0.6 t more annual BC emissions, 0.5 t more annual OC emissions and 63.3 t more annual SO_2 emissions than the baseline scenario. Respectively, annual BC, OC and SO_2 emissions were 118.1 t, 94.5 t and 4487.2 t less in the increased pulpwood use scenario (80PW) than in the baseline scenario. The increased use of energy biomass in scenario 80EB SSB led to greater BC and OC emissions but less SO_2 emissions compared to the baseline scenario, while scenario 80EB LSB led to less BC, OC and SO_2 emissions than the baseline scenario (Table 3 in Article III).

Based on total emissions across Finland compared to the baseline for 2030, IRF_{ARI} was slightly positive for the 80EB SSB (0.004 W m^{-2}) and 80PW (0.001 W m^{-2}) scenarios and negative for the 80EB LSB (−0.006 W m^{-2}) and 80SW (−0.009 W m^{-2}) scenarios (Figure 2). The 80EB SSB scenario, with increased emissions of BC and OC, produced a slightly positive RF for most of Finland, which would indicate that the direct radiative impact of emitted radiation-absorbing BC, in tandem with decreased SO_2 emissions, slightly outweighed the cooling effect of the primarily radiation-scattering OC (Figure 3 in Article III). The 80EB LSB scenario led to weaker radiative effects caused by a smaller reduction in SO_2 emissions and slightly reduced BC and OC emissions, which caused negative IRF_{ARI} over the whole study region. The 80SW scenario, with a minor increase in BC, OC and SO_2 emissions, caused a slightly negative IRF_{ARI}, except for the most southern model grid point. This finding was primarily caused by greater SO_2 emissions, which had contributed to the formation of sunlight-scattering sulphate aerosols. Especially in central Finland, the 80PW scenario displayed slightly positive forcing, even though BC and OC emissions were reduced. This was explained by significantly decreased SO_2 emissions, which reduced the formation of scattering sulphate aerosols.

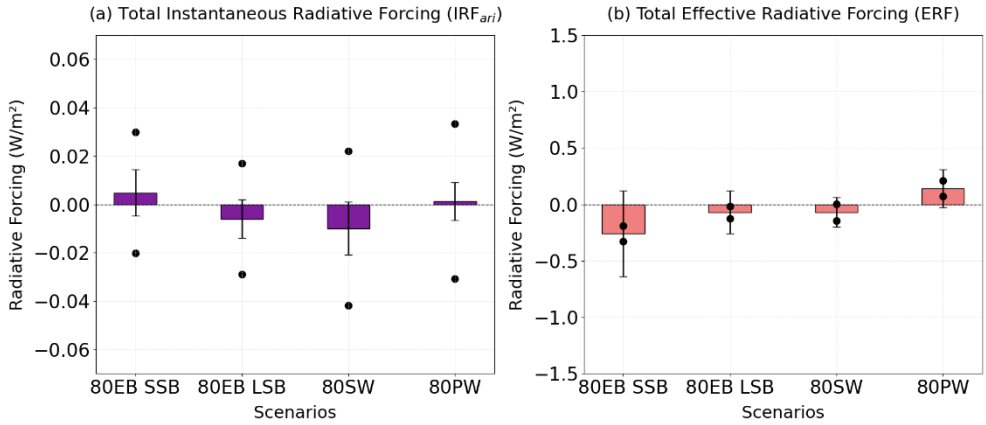

Figure 2. Mean (a) Instantaneous Radiative Forcing (IRF_{ARI}) and (b) Effective Radiative Forcing (ERF) for the increased use of energy biomass combusted in small-scale appliances (80EB SSB), energy biomass combusted in medium- to large-scale boilers (80EB LSB) and sawn wood (80SW) or pulp-based products (80PW) with respect to the baseline scenario, estimated for the whole of Finland. Error bars depict 1-sigma standard deviation of the data calculated across all the grid cells. Solid circles represent the range in interannual variability, which captures the fluctuation of values across different simulation years.

In contrast to IRF_{ARI}, estimated ERF based on total emissions across Finland was only positive for 80PW (0.133 W m^{-2}) and negative for 80EB SSB, 80EB LSB and 80SW (−0.260, −0.077 and −0.074 W m^{-2}, respectively) (Figure 2), which would indicate more pronounced climate effects, compared to IRF_{ARI}, as it encompasses ARI, ACI and rapid atmospheric adjustments. Differing from the IRF_{ARI}, the 80EB SSB scenario resulted in the strongest observed cooling effect over Finland (Figure 4 in article III). This was due to substantially increased BC and OC emissions, which act as cloud condensation nuclei (CCN), thereby enhancing the cloud albedo effect (Twomey Effect) and increase the reflection of incoming solar radiation. In this case, substantial organic aerosol concentrations and subsequent secondary organic aerosol (SOA) formation further brightened clouds, thereby intensifying the cooling effect. The 80EB LSB scenario showed a weaker cooling effect over Finland, caused by modest reductions in BC and OC emissions. The 80SW scenario, in which SO_2, BC and OC emissions all slightly increased, also led to cooling, especially in the central and southern parts of the country. The 80PW scenario exhibited a net warming effect, with the exception of small areas in the northern, western and southern parts of the country. This was due to a significant reduction in SO_2 emissions, which lowered sulphate aerosol concentrations and weakened cloud albedo. As a result, the cooling effect of clouds decreased, and the compensatory cooling from BC and OC emissions was insufficient to offset this change.

4. DISCUSSION

4.1 Evaluation of the approach

In Article I, aerosol emission data for forest biomass, fossil-based materials and fossil fuel use were integrated into an existing LCA tool to improve the life cycle assessments of forest-based production. The use of emission databases enabled comparisons of aerosol emissions from forest- and fossil-based products and energy, using the best available data from existing literature (see section 2.2). Simulated forest management regimes were able to highlight the effects of alternative management regimes, which mainly displayed the alternative and plausible use of forest biomass in Nordic countries. Calculation of aerosol emissions for forest-based products was based on EE, which is strongly dependent on the energy sources used in the calculations and, as such, limits the direct use of the results for different production systems. For instance, energy sources in the production processes could differ considerably between Asian, American and European countries, all of which are globally important producers. However, this was considered in the sensitivity analysis in Article II. In addition, the different technologies used in combustion appliances could affect the aerosol emission outputs.

In article II, DF calculations were applied to the most important aerosol emission components that resulted from the use of forest biomass as a substitute, which has previously received very limited attention. The methodology followed the calculation of DFs for GHGs, as performed by Sathre and O'Connor (2010), and considered the uncertainties that arose from those calculations, especially from EEs and the energy profiles of the products. Allocation of the emissions associated with the by-products to the main product specifically increased the DFs of sawn wood, since combustion produces greater emissions. If the by-products were used to replace fossil fuel-based energy production, better substitution benefits would be gained. However, these benefits are currently minor and typically excluded from the DF calculations of GHGs as well (Hurmekoski et al. 2022, 2023). In addition to variable energy profiles, emission mitigation systems (e.g. filtration systems in industry) affect DFs, as shown in the sensitivity analyses (see section 3.3 in Article II).

In article III, we further utilised DFs to describe the impact of anthropogenic forest-based BC, OC and SO_2 emissions on RF in Finland. For this reason, we compared the baseline scenario (current wood use in Finland: 70 million m^3 $year^{-1}$) to four increased wood use scenarios, in which the annual harvest level was increased by 10 million m^3 and the increased harvest was either used as sawn wood, pulp wood, or as energy biomass combusted either in SSB or LSB. Our approach to only consider direct emissions of BC, OC and SO_2 was justified because these components have the strongest effect on RF among the aerosol emissions (Szopa et al. 2021). As they only remain in the atmosphere from days to weeks (Kuylenstierna et al. 2011), aerosols have mainly local climate impacts, which justifies the local-scale approach in the climate impact assessment (Holanda et al. 2023; Ngoc Trieu et al. 2023). Long-range transport was accounted for in the RF calculations, but emission changes occurred only in Finland. In addition, short-lived climate forcers (SLCFs) can have indirect long-term climate effects as they influence CO_2 levels and carbon sinks through changes in temperature and the climate–carbon feedback loop (Fu et al. 2020) and by altering the CO_2 exchange of forests (Rodrigues et al. 2024).

The ECHAM-HAMMOZ model has a greater sensitivity to aerosol RF than many other current climate models (Neubauer et al. 2019), which should be taken into account when the

results are interpreted. Relying on a single model for simulations and using only one emission inventory as the basis for these simulations might also have led to bias in our findings. Our RF estimates may also contain some uncertainty due to the natural variability of atmospheric circulation because we analysed averages calculated from seven-year simulations. The margins of error in our IRF_{ARI} and ERF estimates (Figure 2) are so wide, encompassing both positive and negative RFs in many scenarios, that they introduce significant uncertainty into the results and our conclusions.

4.2 Effects of forest biomass use on aerosol emissions and subsequent substitution effects (Articles I and II)

The combustion of forest biomass for energy production was found to increase aerosol emissions compared to the use of timber only (Article I). Our studies showed that SSB emitted notably greater amounts of PM (TSP, PM10, PM2.5 and BC) compared to LSB, which is in agreement with studies that have reported that the majority of fine particle emissions in Finland are released from small-scale combustion (Savolahti et al. 2016, 2019; Environment.fi 2022). In 2010, residential wood combustion in Finland was estimated to cause 37% of total PM2.5 emissions and 55% of total BC emissions (Savolahti et al. 2016). However, the emission factors associated with residential wood combustion also exhibit more uncertainty than those for larger boiler plants. The DFs for the energy use of forest biomass (Article II) strongly depended on the combustion devices used during wood combustion, as well as the replaced energy source, and often implied an increase in emissions, especially particulate emissions. Sensitivity analysis showed that possible interannual variation in the unit emissions and the countries where the energy is produced can slightly alter the DFs (Article II). Our findings would suggest that promotion of the forest bioeconomy through an increase in SSB may not be justified if the objective is to mitigate aerosol emissions. However, LSB might be preferable against some energy sources, such as sod peat or light fuel oil, but not coke or gasoil for instance.

In general, the aerosol emissions from sawn wood were somewhat greater than those from alternative construction materials (Articles I and II). However, the inclusion of emissions from the energy use of processing waste substantially increased the emissions associated with sawn wood, which could explain the mostly negative DFs that we observed (Article II). The DFs could have been significantly greater and even positive if by-products use was calculated to displace some fossil fuel-based energy sources. Functional units were found to notably affect the DFs of sawn wood (Article II); those calculated per material tonne and walls had notably smaller values compared to those for slab and column. For sawn wood, the smallest DFs were generally found for NO_x emissions, and DFs for BC were close to zero. Sensitivity analysis indicated that EEs of non-forest-based materials notably affected the DFs of wood, as well as the amount of cement in the concrete mixture.

The production of cardboard also caused significant aerosol emissions when compared to HDPE plastic (Articles I and II). Since the yield in mechanical pulping, characterised by high energy demand, can be as high as 95% (Holmberg and Gustavsson 2007), internal process residues cannot cover all the energy demand, and external energy is needed. The yield in semi-chemical pulping is less than this, and the aerosol emissions of cardboard increased due to the use of processing waste as energy. Significant NO_x, SO_2 and TSP emissions from cardboard production have also been found in other studies (Tsatsis and Koroneos 2009; Metsä Board Corporation 2024). The DFs for cardboard when replacing HDPE (Article II)

were negative for TSP, PM10, PM2.5 and NO_x emissions, and were positive (indicating substitution benefits) for BC, SO_2, and NMVOC emissions. Previous studies have suggested that recyclable corrugated cardboard (CCB) offers environmental benefits, e.g. from the viewpoint of mitigation of climate change and PM formation, when it replaces HDPE plastic in product transportation (Koskela et al. 2014). The findings here align with those results, except for the mitigation of PM formation. If DFs were calculated for the end product (e.g. packing boxes), which may need less cardboard than plastic in mass units, the DFs would have been more favourable for cardboard. The DFs for cardboard were also found to be sensitive to an increase in the EE of plastic (Article II).

Production of wood-based textiles was found to have potential for substitution benefits, depending on the replaced non-wood counterpart (Article II). Primarily, DFs for TSP, PM10 and PM2.5 were negative and implied an increase in emissions: the only exceptions were the viscose–acrylic DFs for TSP and PM10 emissions and viscose–nylon DFs. Instead, DFs for BC were negative for flax, cotton and wool and positive for synthetic textile materials. The DFs for NO_x, SO_2 and NMVOCs were positive aside from viscose–flax DFs for SO_2 and NMVOCs. In this study, flax was the least energy-intensive textile material. The energy profile of non-wood textile production notably altered the DFs of wood-based textiles in the large textile producing countries or regions, which would indicate that they should be calculated separately for each country.

The ongoing transition to give up fossil-based products and energy will fundamentally alter substitution effects, as has also been concluded by Brunet-Navarro et al. (2021). On one hand, the substitution effects of forest-based energy production will degrade in the future because the current trend prefers renewable energy sources, such as wind power and solar energy with no direct aerosol (and GHG) emissions. On the other hand, the substitution effects of forest-based energy production also have potential for improvement, at least over a short timescale. This can be explained by the fact that current small-scale appliances are principally not equipped with particle filtration devices that are, in contrast, mandatory for medium- to large-scale heat and power plants that use solid fuels (Savolahti et al. 2016; Sippula et al. 2019; Mukherjee et al. 2024). Thus, significant potential reductions in aerosol emissions can be found in SSB, especially through the introduction of efficient filtration systems. In the EU, there is ongoing development of legislative work (for SSB especially), which may introduce requirements for more advanced particle emission control systems and other technological solutions to decrease aerosol emissions from the combustion of biomass (Commission Regulation (EU) 2015/1185; European Commission 2024; European Commission 2025). The substitution effects of forest-based materials may also benefit from modern innovations; this can be clearly seen in the case of wood-based textiles, where both aerosol and GHG emissions will likely reduce in the future, which could make more positive substitution effects achievable (Metsä Spring 2021; Spinnova 2023).

The results presented in Articles I and II highlighted that aerosol emissions vary significantly depending on how forest biomass is used. Area-based and mass-based analyses under alternative management regimes were found to be similar (Article I). This variation in aerosol emissions was also supported by the different amounts of aerosols emitted by the increased forest biomass use scenarios in Article III, which resulted in clearly different climate impacts between the scenarios. As lifecycle aerosol emissions from forest-based materials and energy significantly differed from those of their fossil-based counterparts, hypothesis I of this thesis was proven correct. Hypothesis II, in turn, was confirmed by the finding that the substitution benefits of forest biomass use were not found as often for aerosol emissions as for GHG emissions.

4.3 Effects of increased forest biomass use on aerosol emissions and climate change mitigation potential in Finland (Article III)

The research design in Article III differed from Articles I and II, as it did not focus solely on aerosol quantities, and the analysed emission components were also partly different. Therefore, increased use of forest biomass for energy production and sawn wood were found to produce climate-cooling aerosol emissions, whereas the replacement of polyester and HDPE plastic with viscose-based textiles and cardboard reduced aerosol emissions. Consequently, IRFs for the 80EB LSB and 80SW scenarios projected cooling effects on the climate, whereas in the 80EB SSB and 80PW scenarios, they projected warming in most parts of Finland. The difference observed between LSB and SSB was caused by much greater emissions of carbonaceous aerosols in the latter, which led to an increase in IRF because of the positive RF associated with BC (Szopa et al. 2021). Conversely, changes in the ERFs, which also included subsequent atmospheric responses, showed that SSB had the greatest potential for climate cooling, likely due to cooling from cloud processes caused by strong BC and OC emissions (Kanakidou et al. 2005; Koch and Del Genio 2010). For the majority of Finland, the ERF only increased in the 80PW scenario, which was mainly caused by the large reduction in SO_2 emissions. On average, the increased forest biomass use scenarios led to a decrease in IRF and ERF in Finland, thereby implying a cooling effect on the climate, which is consistent with the general perception that aerosols contribute to climate cooling (Szopa et al. 2021). The clear differences observed in both IRF and ERF across the alternative scenarios would indicate that careful consideration of how forest biomass is used can support climate change mitigation efforts, which confirmed hypothesis III.

The rationale for prioritising the energy use of forest biomass is, however, doubtful due to the CO_2 emissions that are immediately released during combustion (Haberl et al. 2012), as CO_2 has the greatest RF of all anthropogenic emissions (IPCC 2023). This is consistent with the degradation of ambient air quality and consequent health risks caused by strong particulate emissions from the energy use of forest (Kennedy 2007; Lepeule et al. 2012; Shiraiwa et al. 2017; Arfin et al. 2023; Villarroel et al. 2024). The phasing out of coal use in Finland by 2030 (Finnish Government 2019), as well as the reduction in the use of peat as energy in the future (Ministry of Economic Affairs and Employment of Finland 2022), will further weaken the position of forest-based energy relative to other alternative sources.

From the viewpoint of GHG emissions, production of long-lived wood-based products is often justified, especially due to the longer life cycle of the product, minimised emissions from the end-of-life stage, the production of new products, forest management methods that favour carbon sequestration, and the capability of forest-based products to act as carbon stores (Pingoud et al. 2010; Sathre and O'Connor 2010; Lippke et al. 2011; Geng et al. 2017; Hetemäki et al. 2022). This was supported in our results with regard to aerosol emissions as it also decreased IRF and ERF (Article III). Thus, even if a significant portion of roundwood is combusted soon after harvesting as a by-product, we suggest that the increased use of sawn wood could be the most sustainable way to use forest biomass. However, reducing forest harvest levels in Finland has been suggested as a tool to support carbon neutrality (Natural Resources Institute Finland 2023b; Mosley et al. 2024) and they may also contribute to cooling the climate by increasing biogenic secondary organic aerosols (SOA) (Kalliokoski et al. 2020).

Since the effects of aerosol emissions on climate can be either warming or cooling, and include significant uncertainty, the influence of increasing aerosol emissions due to the use of forest biomass is anything but unambiguous. Furthermore, the consideration of climate

effects of forest biomass use is even more complicated due to the interplay of various emission components in the atmosphere. For instance, an increase in NO_x and NMVOC emissions contributes to greater ozone formation, while combustion-related NMVOCs can also be involved in the formation of secondary aerosols in the atmosphere (Wu et al. 2020). Further, the SO_2, NO_x and particle emissions that affect cloud formation lead to complex, most likely cooling, effects on the climate (Spracklen et al. 2008; Rosenfeld et al. 2014). Moreover, alterations in aerosol emissions have a more immediate impact on the climate compared to changes in CO_2 or CH_4 emissions, due to the shorter atmospheric residence time compared to long-lived GHGs (Szopa et al. 2021). The DFs implied an increase in PM emissions due to the use of forest-based materials, while SO_2 emissions often decreased (Article II), as also reported by Petersen and Solberg (2005). Even if an increase in aerosol emissions could cool the climate through ACI, it would probably not offset the warming caused by rising GHG emissions.

5. CONCLUSIONS

This thesis has shown that consideration of aerosol emissions can notably alter our understanding of the environmental consequences of forest biomass use, compared to when only GHGs are considered. Frequently, the use of forest biomass is associated with strong aerosol emissions, especially if the forest biomass is combusted in small-scale appliances, and forest-based energy production generally leads to greater aerosol emissions than allocating all biomass harvest to timber production when only by-products are used for combustion. The use of forest biomass can cause strong emissions of BC, for instance, which effectively absorbs solar radiation. To minimise the drawbacks in climate aims and air quality, the inclusion of aerosol emissions in LCAs of forest biomass is critical. The environmental burden of forest biomass use can significantly be reduced by carefully considering how it is used.

The substitution effects of forest biomass are likely to alter in the future, especially because of the shift towards carbon neutrality and the reduction of fossil fuel-based energy, along with technological advancements that affect aerosol emissions. As such, forest-based energy is usually seen as an interphase instead of the final goal, even though technological progress could partly offset the expected long-term deterioration in the substitution effects of forest biomass use, at least in the near future. As it is heavily dependent on the energy transition, the eventual development of aerosol substitution effects over time is difficult to estimate. This emphasises the need for established DF estimation methods, supported by more detailed empirical aerosol emission data. The complex interactions of aerosols in the atmosphere also make it difficult to assess the total substitution effects of forest biomass when the overall effects of air pollution are considered.

As both harvesting amount and the way forest biomass is used caused clear differences in IRF and ERF (Article III), the climate effects of anthropogenic aerosols should be comprehensively considered together with GHGs in the context of forest-based climate change mitigation. Given the observed potential for reduction in RFs caused by a change in aerosol emissions, it can be suggested that utilising forest biomass to replace fossil-based products does offer climate change mitigation potential. Based on the findings in this thesis and our existing knowledge of GHG emissions, it can be concluded that the most sustainable overall climate benefits would be achieved by prioritising the production of long-lived wood-based products. The results of this thesis will open new perspectives to forest bioeconomy-related research, as well as to assessments of the environmental consequences of future forest biomass-based solutions.

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Corrigendum to Article **I**:

In the published version of this article, Figures 3 to 5 are incorrectly arranged. The figure originally intended for Figure 3 is entirely missing. The figure currently labelled as Figure 3 should appear as Figure 4, and the figure currently shown as Figure 4 should appear as Figure 5. The figure captions and in-text references remain in the correct order and should not be altered.

For completeness, the correct figure for Figure 3 is provided below in this dissertation, following this note.

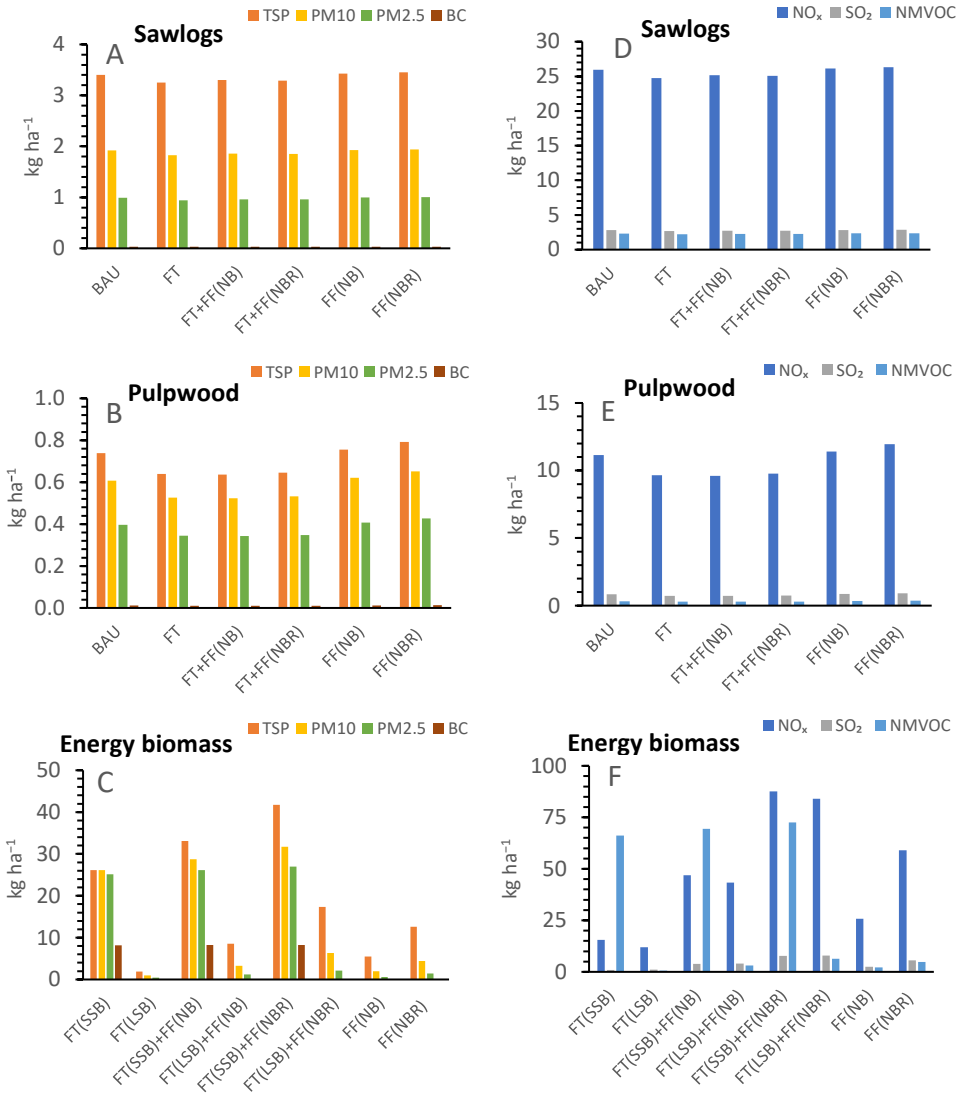

Fig. 3. Aerosol emissions (kg ha^{-1}) from the use of sawlogs (A and D), pulpwood (B and E), and energy biomass (C and F) for TSP, PM10 and PM2.5 (A–C) and BC, NO_x, SO_2 and NMVOC (D–F). Abbreviations for management regimes are explained in Table 1.