Climate effects of a forestry company

– including biogenic carbon fluxes and substitution effects (2021 update)

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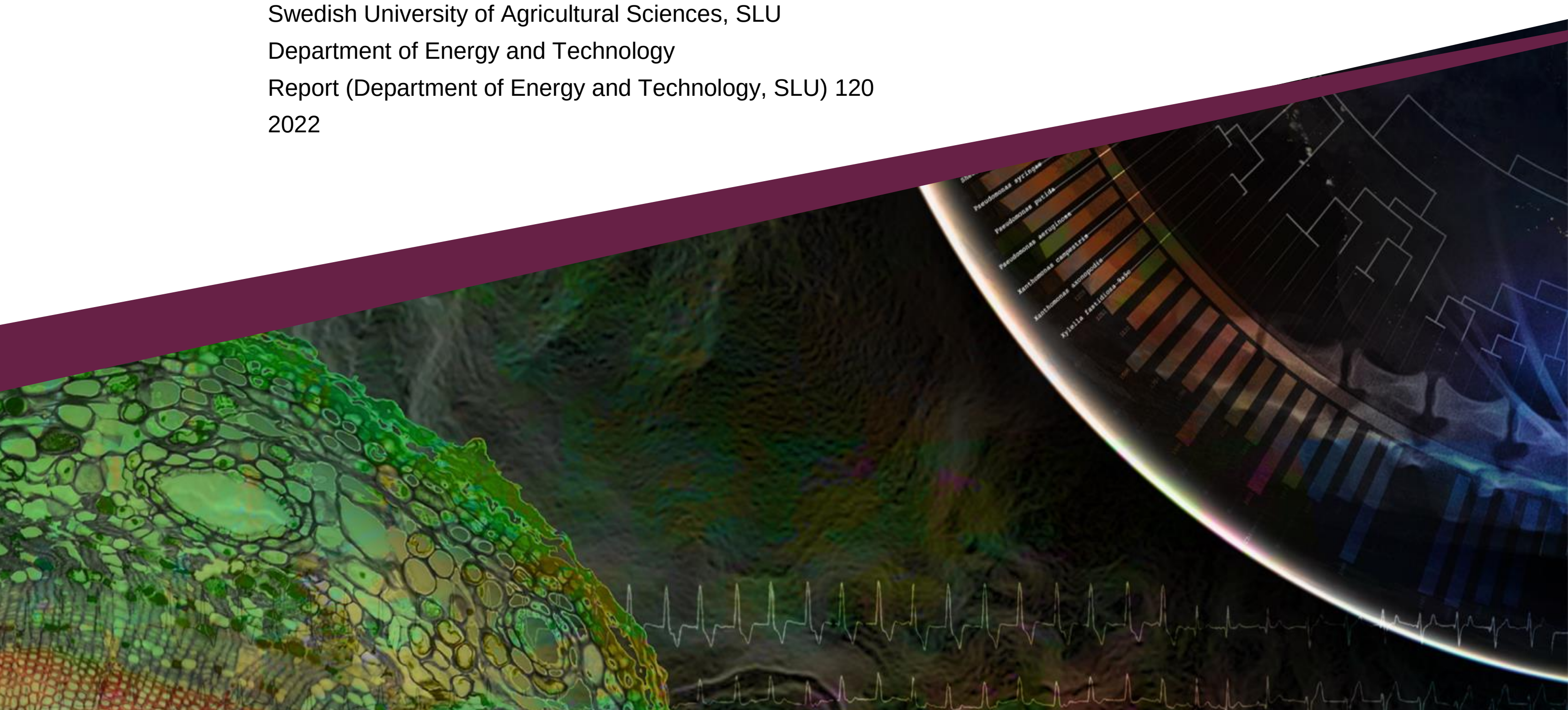

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Abstract

Forestry play an important role in the bioeconomy, and will continues to do so in the future, by providing wood fibres for biomaterial and bioenergy that substitute for fossil-based alternatives, while at the same time storing carbon in forests and harvested wood products. However, there are contradictory opinions on the climate change mitigation potential of forestry. Stora Enso, an international forestry company, has the ambition to improve its climate impact assessment at corporate level.

In this work, a system perspective was applied, where greenhouse gas emissions from value chains, biogenic carbon fluxes from forest land owned or leased by Stora Enso and temporarily stored in harvested wood products, and the substitution effect, i.e. avoided emissions from substituted products and energy were considered. Furthermore, new substitution factors for pulp and paper products were developed.

The current report is an update of the original report, published in 2020 (Hammar et. al. 2020), based on production and value chain emissions data for the year 2021, as well as Eucalyptus plantation area as of December 2020. Overall changes in greenhouse gas fluxes relative the ones published in Hammar et al. (2020) are minor. The estimated climate effect at corporate level for 2021 is a net removal of -11.0 million Mg CO2-eq yr-1 (i.e. a climate benefit) for the year 2021 (compared to -11.5 million Mg CO2-eq yr-1 for the year 2019) when considering value chain emissions, biogenic carbon fluxes from forest land and harvested wood products, and avoided emissions from substitution. Uptake of biogenic carbon counteracted around 40% of the value chain emissions (10.2 million Mg CO2-eq yr-1), while the largest climate benefit (removal of 17.2 million Mg CO2-eq) was due to substitution of more greenhouse gas-intensive products.

The same substitution factors developed in Hammar et al. (2020) for pulp and paper products were applied in the climate impact calculation at company level. Possible improvements for future studies inclued, e.g., the assessment of the impact of cascading wood use in substitution calculations.

Keywords: climate impact, life cycle assessment (LCA), biogenic carbon, forestry, substitution, soil organic carbon (SOC)

Preface

This project was part of a larger strategic research collaboration between Stora Enso and the Swedish University of Agricultural Sciences (SLU). The original work was funded by Stora Enso and performed in the period November 2019 to October 2020 by researchers at SLU, with additional input on forest simulations from Treesys and Simosol. An update was performed during January 2022, based on production and value chain emissions data for the year 2021 as well as Eucalyptus plantation area as of December 2020.

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Abbreviations

C	Carbon
CH_4	Methane
CO_2-eq	Carbon dioxide equivalents
EoL	End of life
EPS	Expanded polystyrene
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
HDPE	High-density polyethylene
HWP	Harvested wood product
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
LPB	Liquid packaging board
Mg	Megagram (metric tonne)
N_2O	Nitrous oxide
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
sub	Solid under bark
SE	Substitution effect
SF	Substitution factor
UHT	Ultra high temperature
VCE	Value chain emission

1 Introduction

Forests act as an important carbon sink by sequestering large quantities of carbon in standing biomass and soil. A growing forest removes carbon dioxide (CO_2) from the atmosphere, and this sequestered carbon can thereafter be transferred to the soil via litter, root turnover or dead wood. Carbon is also removed from the forest by natural decomposition or tree harvesting, and thus how forests are managed plays an important role for the carbon balance, and consequently the climate (Nabuurs *et al.*, 2007). In sustainably managed forests, new trees are planted that once again sequester CO_2 from the atmosphere, as part of a natural carbon cycle.

The important role of forests in climate change mitigation strategies is highlighted in, notably, the Swedish climate policy framework, where additional measures to increase uptake of CO_2 in forest and soils count towards the climate target of reaching negative greenhouse gas emissions by 2045 (Swedish EPA, 2017). The importance of forest biomass is also acknowledged in the EU bioeconomy strategy, which highlights the potential for forest biomass to contribute to meeting the Paris Agreement commitments (European Commission, 2018), and, more recently, the 'Fit for 55' package of proposals (European Commission 2021), with the overriding objective of reducing EU net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 to achieve climate neutrality, i.e., net zero greenhouse gas emissions, by 2050. There is an ongoing, intense, debate over the best forest management practices from a climate impact perspective, not the least in Sweden.

Harvesting forest biomass does not release the CO_2 back to the atmosphere instantaneously. Instead, the carbon is stored in the harvested wood products for a certain period, the length of which depends on the use of the wood and the end-of-life management. Wood materials can be reused and recycled, a process referred to as cascading wood use, which prolongs the carbon storage time and increases the resource efficiency. The cascading wood use process can either be single-stage, where the wood is used for one product followed by energy recovery, or multi-stage, where the raw material is used for at least two products or materials, after which it is either energy recovered or disposed of (Thonemann & Schumann, 2018).

An additional aspect to consider when determining the climate impact of using forest biomass is that wood can replace non-renewable materials with high climate impact. The avoided emissions from the replaced products is referred to as the substitution effect, which describes the amount of greenhouse gas emissions avoided. The substitution effect of specific wood products, which is described by a substitution factor (also called displacement factor), varies depending on the emission intensity of the wood product and the replaced product (Sathre & O'Connor, 2010).

The substitution effect of wood products has been assessed in previous studies, but mainly with the focus on solid wood products used for building materials and bioenergy. Cascading wood use and recycling of substituted products bring additional complexity to the analysis and are often overlooked (Leskinen *et al.*, 2018). There is a wide range of paper and pulp products, with varying uses and potential substitution effects, but wood-based products from the pulp and paper industry have not been assessed to the same degree as building materials.

Stora Enso is an international forestry company producing a range of wood-based products such as packaging, biomaterials, paper and wooden constructions. The company has the ambition to improve its climate reporting, in particular regarding the substitution effect of pulp and paper products and the biogenic carbon fluxes from using forest biomass.

To assess the overall climate impact of a forestry company, a system perspective is required where forest carbon stock changes, temporary carbon storage in wood products, value chain emissions and avoided emissions from substitution are considered. Life cycle assessment (LCA) is the most common method for assessing the climate impact of a product or service throughout its entire life (ISO 14040, 2006; ISO 14044, 2006). When using LCA, the goal is to include the full lifespan of the assessed product, referred to as cradle-to-grave, to avoid burden shifting between different life phases. The standardised method comprises four phases: (1) goal and scope definition; (2) life cycle inventory analysis; (3) life cycle impact assessment; and (4) interpretation of results.

1.1 Goal and scope

The overall goal of the present study was to determine the annual climate impact of Stora Enso's product portfolio at company level, including value chain emissions, forest carbon stock, carbon in harvested wood products and avoided emissions from substitution. New substitution factors were developed if required for the climate impact reporting. Specific objectives of the study were to:

1. Develop new substitution factors for:
   a) Pulp and paper products.
2. Update the substitution factor for:

    a) Bioenergy.
3. Calculate biogenic carbon fluxes for:
    a) Forest carbon stock changes in forest owned or leased by Stora Enso.
    b) Temporary carbon storage in harvested wood products.
4. Calculate Stora Enso’s climate impact at company level, including the substitution effect and biogenic carbon fluxes.

The climate impact was calculated for Stora Enso’s product portfolio during one year, including both wood harvested from forests owned or leased by Stora Enso and purchased wood. The current study is an update, using data from Stora Enso regarding production volumes and value chain emissions for the year 2021. A change in Eucalyptus plantation area since the original report was also taken into consideration.

2 Method

2.1 System boundaries

The climate impact assessment included forest carbon stock changes, carbon stored in harvested wood products, value chain emissions and avoided emissions from substitution (Figure 1). Forest carbon stock changes for tree plantations of Stora Enso's joint ventures in Brazil, Uruguay and China, and Stora Enso's forest land in Sweden and associated company Tornator's forest land in Finland, were included in the assessment (see section *2.4 Forest carbon stock*). Temporary carbon storage in harvested wood products was included following the methodology in Rüter *et al.* (2019) (see section *2.5 Harvested wood products*).

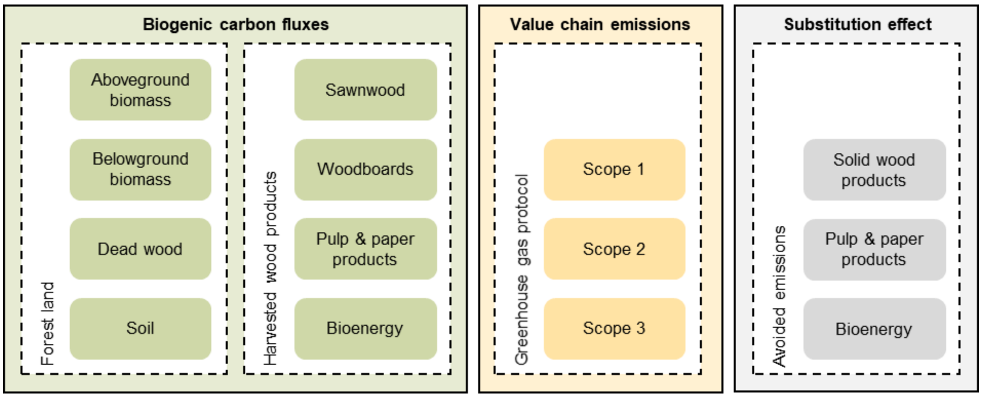

Figure 1. System boundaries set for climate impact assessment of Stora Enso at company level.

Data on value chain emissions at company level were taken from Stora Enso's yearly climate reporting (Stora Enso, 2019c), which follows the greenhouse gas protocol standard (WRI & WBCSD, 2015) (see section *2.6 Value chain emissions*). New substitution factors for selected pulp and paper products and bioenergy based on wood chips from forest residues were calculated, while the substitution factor for solid wood products was based on previous studies (see section *2.3 Development of substitution factors*). Stora Enso is an international company operating on the global market, but its largest market share is in Europe. Therefore, a European perspective was applied for calculating the substitution factors.

2.2 Climate impact assessment

The climate impact was calculated in terms of global warming potential (GWP), which converts greenhouse gases into carbon dioxide equivalents (CO_2-eq). Beside CO_2, emissions of nitrous oxide (N_2O) and methane (CH_4) were considered. These greenhouse gases have differing potential to warm the climate, due to differences in atmospheric lifetime and radiative efficiency (Table 1).

Table 1. Global warming potential in a 100-year perspective (GWP_{100}) of nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) (Myhre *et al.*, 2013)

	N_2O	CH_4	CO_2
Fossil/biogenic	265	30/28	1

The total climate impact (in Mg CO_2-eq) was calculated as:

$$Climate\ impact = VCE + \Delta C_{forest} + \Delta C_{HWP} - SE \quad (1)$$

where *VCE* are value chain emissions at company level, ΔC_{forest} is the biogenic carbon flux from forests, ΔC_{HWP} is the biogenic carbon flux from temporary carbon storage in harvested wood products and *SE* is the substitution effect. A negative value for climate impact represents a climate benefit.

2.3 Development of substitution factors

2.3.1 Definition of substitution factor

There are different definitions of substitution factor (SF) (Leskinen *et al.*, 2018; Sathre & O'Connor, 2010). In this study, substitution factor was defined as the amount of fossil greenhouse gas emissions that a wood-based product substitutes, expressed in Mg (metric tons) fossil carbon per Mg carbon stored in the wood products (Mg C Mg^{-1} C):

$$\mathrm{SF} = \frac{(GHG_{non-wood} - GHG_{wood}) \cdot \frac{12}{44}}{C_{wood} - C_{non-wood}} \quad (2)$$

where GHG_{wood} is fossil greenhouse gas emissions (in CO_2-eq) from the production chain for wood-based products, $GHG_{non-wood}$ is fossil greenhouse gas emissions from the production chain of replaced products, C_{wood} is the biogenic carbon content in the wood product, $C_{non-wood}$ is the biogenic carbon in the replaced product, and 12/44 is the molecular mass ratio of carbon to CO_2, which converts CO_2-eq into carbon.

The substitution factor can be further divided for the different life cycle stages of the wood-based product (Figure 2). Four phases are described in Leskinen *et al.*

(2018): $SF_{production}$, which includes the production phase, *e.g.* forestry operations, processing and transportation to customers; SF_{use}, which includes the use and re-use phase; $SF_{cascading}$, which includes material recycling into new products; and SF_{EoL}, which is the end-of-life phase where the material is either energy recovered or disposed of.

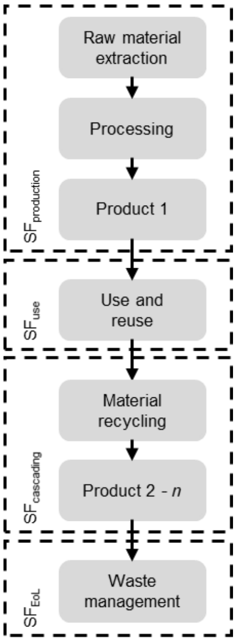

Figure 2. Simplified flowchart of life cycle stages of a wood-based product (SF = substitution factor, EoL = end of life).

In this study, two substitution factors were calculated, $SF_{production}$ and SF_{EoL}, where $SF_{production}$ was divided between Stora Enso's value chain emissions (cradle-to-gate) and emissions occurring downstream from the company's factory gate (gate-to-EoL). This was to avoid double counting, since the value chain emissions of Stora Enso are reported separately from the substitution effect (following the greenhouse gas protocol, see Figure 1). Substitution factors for the use phase and wood cascading were not calculated, since no cascading product substitution effect was identified for the products assessed in this study. However, $SF_{production}$ was adjusted for the effect of material recycling, to avoid overestimation of the substitution factor (described in more detail in sections *2.3.3 Liquid packaging board* and *2.3.4 Corrugated board*). The SF_{EoL} factor included the end-of-life emissions from incineration and energy substitution, which was allocated to the virgin wood fibre.

The total substitution effect (Mg CO_2-eq) at company level during one year was calculated as:

$$SE = \frac{44}{12} \cdot \sum_{k=1}^{n} SF_k \cdot P_k \quad (3)$$

where *SF* is the total substitution factor (*i.e.* sum of $SF_{production}$ and SF_{EoL}) for the specific product, *P* is the production volume (in Mg biogenic carbon), *k* is the specific product category, *n* is the number of product categories, and 44/12 converts carbon into CO_2.

The substitution factors currently used by Stora Enso for its annual climate reporting are 0.7 Mg C Mg^{-1} C for bioenergy, 0.7 Mg C Mg^{-1} C for paper and pulp products and 1.5 Mg C Mg^{-1} C for solid wood products (based on Holmgren and Kolar (2019)).

2.3.2 Identified products

Substitution factors were developed for pulp and paper products and bioenergy, while a literature value was used for solid wood products. Not all pulp and paper products were identified as having a product substitution effect, so in those cases only the energy substitution at the end of life management was considered (Figure 3). Only virgin wood fibres were calculated as having an energy substitution effect, to avoid double counting (*i.e.* the energy substitution at end-of-life was allocated to the virgin fibre).

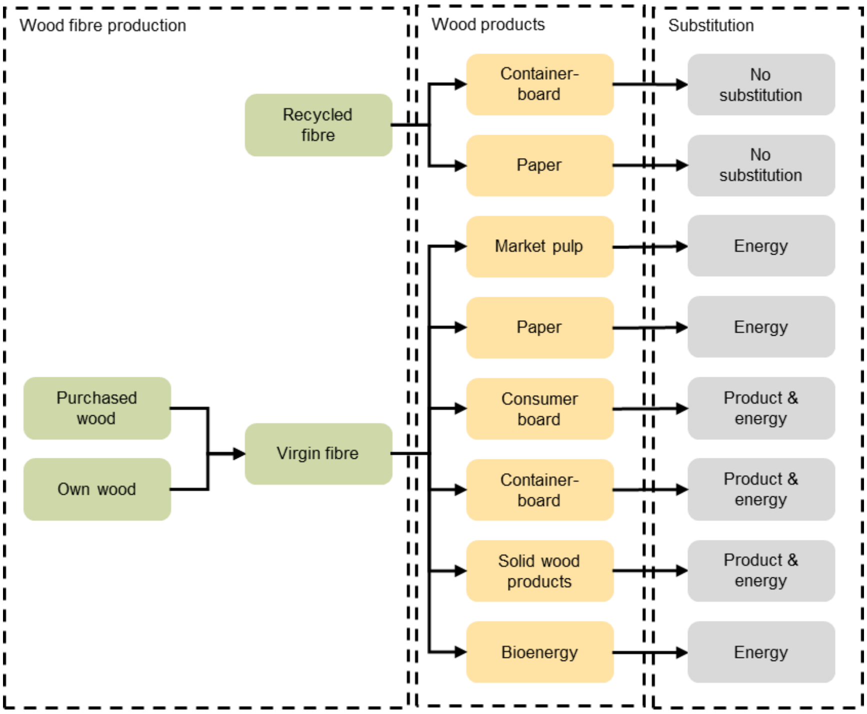

Figure 3. Simplified flowchart of product/energy substitution by wood-based products produced by Stora Enso.

Two paper and pulp products were identified as substituting a fossil-based product, namely liquid packaging board (consumer board) and corrugated board (containerboard) (Table 2). Liquid packaging board can be used for different food products. In this assessment, a beverage carton for ultra high temperature (UHT) milk that can substitute polyethylene terephthalate (PET) bottles was selected.

Table 2. Overview of wood-based products identified as substituting a fossil-based product in this assessment

	Wood-based product	Substituted product
Consumer board	Liquid packaging board (beverage carton)	PET bottle
Containerboard	Corrugated board (EcoFishBox^{TM})	Expanded polystyrene packaging
Other pulp and paper products[a]	Energy recovery only (heat & power)	Natural gas & electricity mix
Bioenergy	Wood chips (heat & power)	Natural gas & electricity mix

[a]No product substitution identified (market pulp, paper, part of consumer board and containerboard).

The recently developed EcoFishBox^{TM}, which is produced from corrugated board and can substitute expanded polystyrene (EPS) boxes for transporting fish, was assessed. The EcoFishBox^{TM} is currently produced in relatively small quantities, and therefore the production volume was varied in a sensitivity analysis to assess the future potential. A substitution factor for bioenergy was calculated based on heat and power produced from wood chips. The bioenergy and the energy recovered from the studied wood products were assumed to substitute an electricity mix and heat from natural gas.

2.3.3 Liquid packaging board

Liquid packaging board (LPB) can be used for food packaging, *e.g.* different types of drinks. The paperboard is either coated with polymer for barrier properties or laminated to increase the lifetime of the beverage (Stora Enso, 2019a). A 1000-mL beverage carton for UHT milk produced from ambient liquid packaging board was selected in this assessment, and was compared with a full barrier PET bottle. Liquid packaging board was assumed to be produced from virgin pulpwood and then transported to a beverage carton box production facility for further processing (Figure 4).

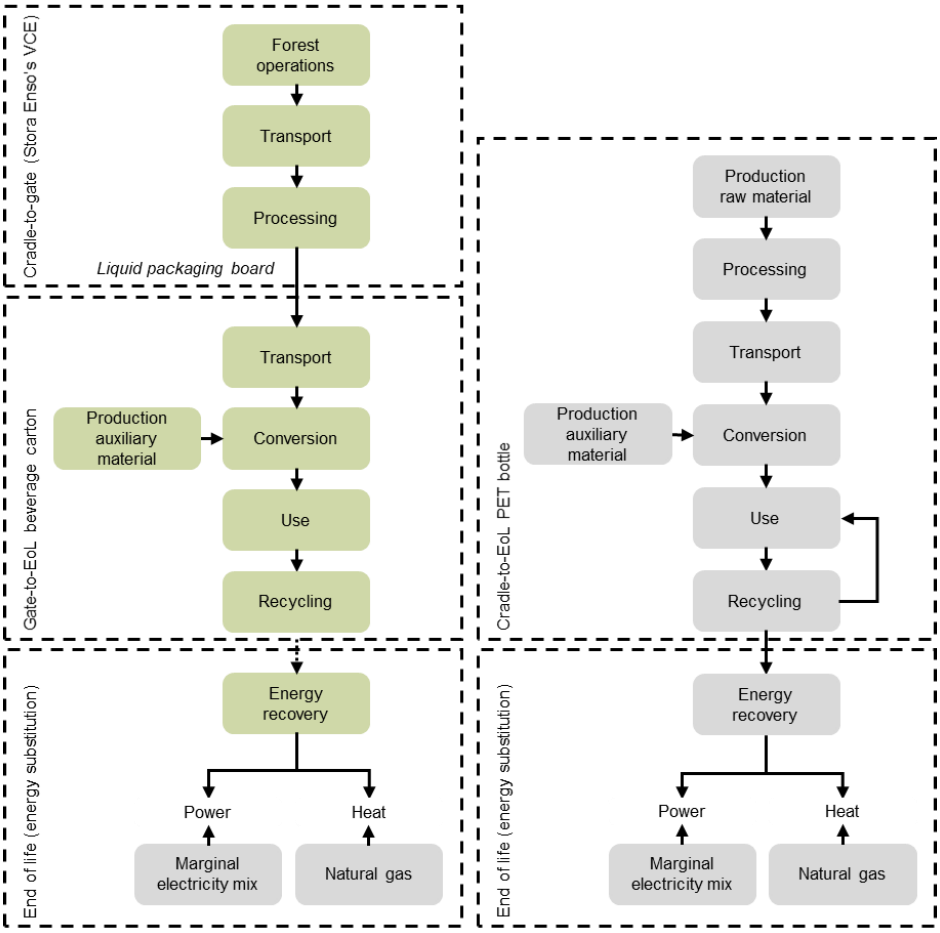

Figure 4. Flowchart of emissions from production of a beverage carton from liquid packaging board (green boxes), divided into Stora Enso's value chain emissions (VCE) and gate-to-end of life (EoL) emissions, and system boundaries for the replaced PET bottle and energy substitution (grey boxes).

Emissions from production of auxiliary materials were included for both packages. Data on fossil greenhouse gas emissions for producing and transporting the materials were taken from Ecoinvent (Wernet *et al.*, 2016) and previous studies, or obtained from Stora Enso. The use phase (*i.e.* filling of package and transport to consumer) and distribution to the retailer were excluded from the assessment.

According to European statistics, 86% of paper and cardboard packaging was recycled in 2017 (Eurostat, 2020a). For beverage cartons sold in the EU, 48% was recycled in the same year (ACE, 2020). However, recycled liquid packaging board is currently not used for food packaging and, since no additional product substitution was identified in this assessment, recycling of liquid packaging board was excluded from the assessment.

Plastic packaging has a lower recycling rate, around 41% in the European Union (Eurostat, 2020a). However, PET bottles have a higher recycling rate than other plastic packaging, and the recycled material can be used for food packaging. In Sweden, the recycling rate for PET bottles is 83% (SCB, 2019), while the recycling rate at European level is around 52% (EUNOMIA, 2020). Since the recycled PET can be used for food packaging, the recycling rate of PET bottles was considered in the assessment (Figure 5), to avoid overestimation of the substitution effect. Recycling of auxiliary materials into new products was not considered and only energy recovery through incineration was assumed as an end-of-life management option.

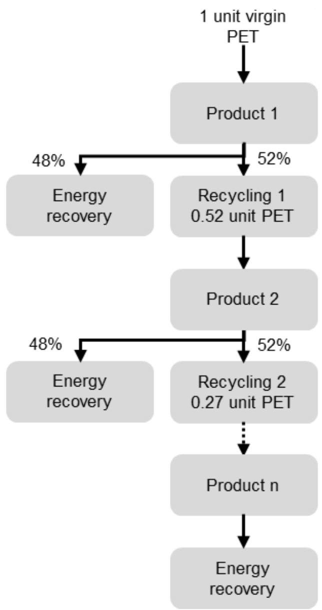

Figure 5. Recycling flowchart for PET bottles.

The total amount of available PET material (virgin and recycled) was calculated as the sum of a geometric series where *n* goes to infinity:

$$x + xa + xa^2 + xa^3 + \cdots = \sum_{k=0}^{\infty} xa^k = \frac{x}{1-a}, \text{ for } |a| < 1 \qquad (4)$$

which for this case was described by:

$$M_{total} = \sum_{k=0}^{\infty} M_{virgin} \cdot a^k = \frac{M_{virgin}}{1-a} \qquad (5)$$

where M_{total} is total available material (recycled and virgin material), M_{virgin} is initial virgin material, a is the recycling rate, and k is the number of uses. The recycled material is then:

$$M_{recycled} = M_{total} - M_{virgin} \qquad (6)$$

This gives 1.1 units of recycled PET per unit of virgin material (Table 3).

Table 3. Virgin, recycled and total material units used for beverage carton and PET bottle (calculated using Equations 5 and 6)

	Recycling rate (a)	Virgin mass (M_{virgin})	Recycled mass ($M_{recycled}$)	Total mass (M_{total})
Beverage carton[a]	-	1.0	-	1.0
PET bottle	0.52	1.0	1.1	2.1

[a]Excluding recycling used for other products than beverage carton.

Since a PET bottle can be recycled and used for new bottles, a replacement rate was calculated for the beverage carton:

$$R = \frac{M_{wood}}{M_{non-wood}} \quad (7)$$

where R is replacement rate of the wood product (beverage carton from liquid packaging board), M_{wood} is wood material (virgin LPB) and $M_{non\text{-}wood}$ is non-wood material (virgin and recycled PET).

On inserting the values from Table 3 into Equation 7, a replacement rate of 0.5 was obtained, meaning that one beverage carton produced from virgin LPB replaces 0.5 virgin PET bottle. Calculation of the substitution factor for the beverage carton (SF_{BC}, in Mg C Mg C^{-1}) according to Equation 2 was adjusted with the replacement rate:

$$\mathrm{SF}_{BC} = \frac{(GHG_{non-wood} \cdot R - GHG_{wood}) \cdot \frac{12}{44}}{C_{wood} - C_{non-wood} \cdot R} \quad (8)$$

The energy recovery emissions and avoided emissions from energy substitution are described in section *2.3.7 Energy recovery and substitution*.

2.3.4 Corrugated board

Corrugated board is produced from containerboard and consists of at least three layers, two outer layers called liner (kraftliner if virgin material and testliner if recycled material) and one inner layer called corrugated or fluting medium. Corrugated board is mostly used for packaging material and boxes for transportation, and no substituted product was identified in this assessment. However, energy is recovered in the end-of-life management, and can substitute heat and power (described in section *2.3.5 Other pulp and paper products*). In addition, the recently developed EcoFishBox™ can replace expanded polystyrene (EPS) boxes for transporting fish. Production is currently relatively small-scale, but it has potential to increase in the future. A substitution factor was therefore calculated for the EcoFishBox™, where the potential production volume was varied in a sensitivity analysis (with no production as a baseline scenario).

Emissions data for the EcoFishBox™ and an EPS box were retrieved from a previous study by LCA consulting and Stora Enso (2018) (excluding the recycling and energy recovery phase due to different assumptions in this assessment), where average values for the 20 kg fish box were used for the assessment (Figure 6).

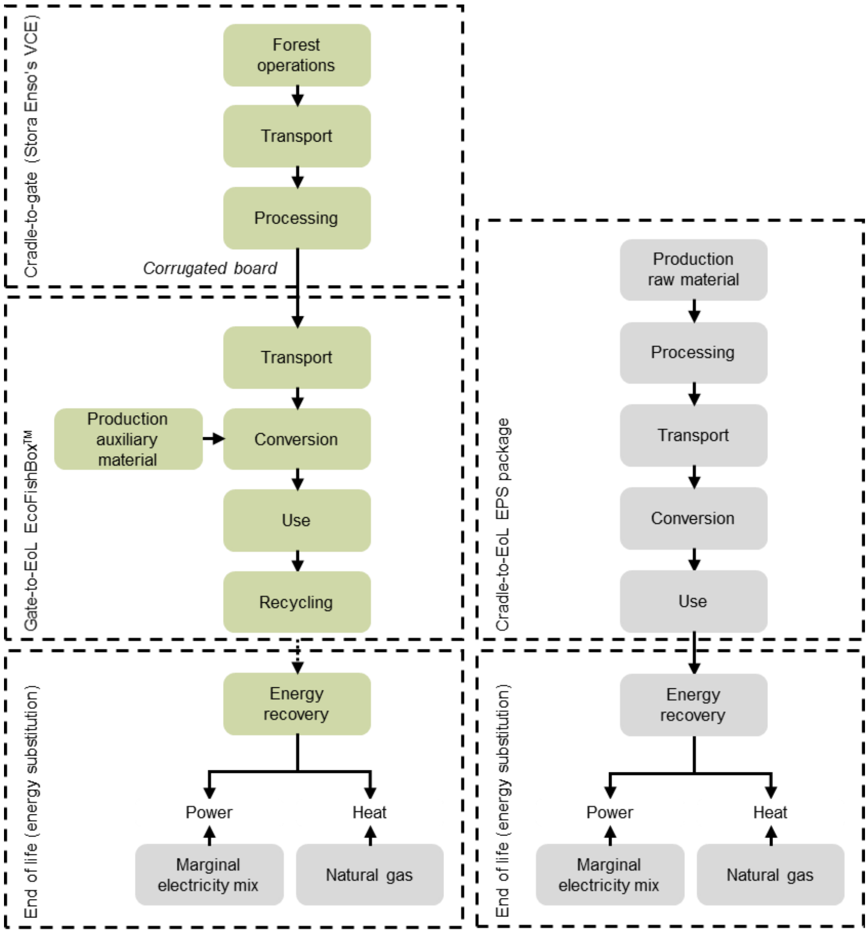

Figure 6. Flowchart of emissions from production of corrugated board used for the EcoFishBox™ (green boxes), divided into Stora Enso's value chain emissions (VCE) and gate-to-end of life (EoL) emissions, and replaced expanded polystyrene (EPS) boxes and energy substitution (grey boxes).

The corrugated board can be recycled, but only virgin material was assumed to be used for the EcoFishBox™ since the recycled corrugated board is used for other purposes, *e.g.* as packaging material for non-food products. Recycling of the corrugated board was therefore not included in the assessment. Expanded polystyrene boxes are generally not recycled and the recycling rate was therefore set to zero. Since only virgin material was used for both types of fish boxes, the replacement rate was one, *i.e.* one EcoFishBox™ replaced one EPS box.

Emissions from energy recovery and energy substitution are described in section *2.3.7 Energy recovery and substitution*.

2.3.5 Other pulp and paper products

For the pulp and paper products where no product substitution was identified, *i.e.* there was no clear alternative product that the pulp and paper product could replace, an energy substitution factor was calculated (SF_{EoL}) (Figure 7). The products with no identified product substitution were market pulp, paper, consumer board (excluding liquid packaging board) and container board (excluding corrugated board for EcoFishBox^{TM}). The product category included well-established products that have been on the market for a long time and dominate the market, and thus no additional product substitution was considered realistic for the majority of the production volume. Since the end-product of these product categories varies, a proxy based on paper produced from chemical pulp was calculated.

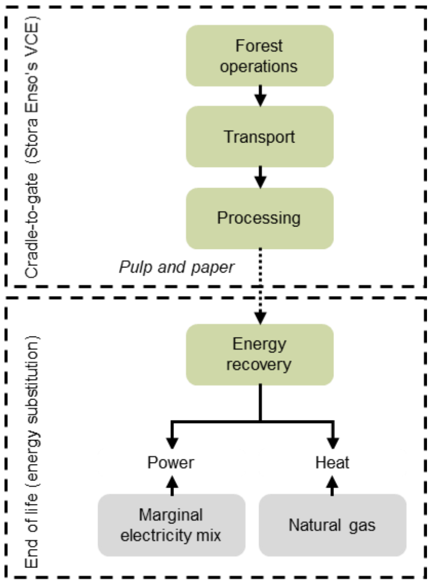

Figure 7. Flowchart of emissions from paper and pulp products when only considering energy substitution, divided into Stora Enso's value chain emissions (VCE) and end-of-life emissions (grey boxes).

Data on the value chain emissions up to the factory gate were retrieved from Stora Enso and Wernet *et al.* (2016). Emissions from energy recovery and energy substitution are described in section *2.3.7 Energy recovery and substitution*.

2.3.6 Bioenergy

A bioenergy substitution factor was calculated based on wood chips produced from forest residues (tops and branches) harvested at final felling in Sweden. Emissions for forwarding, chipping forest residues directly at the roadside, and transport to a combined heat and power (CHP) plant for combustion were included, based on emissions data from Hammar *et al.* (2015) and Lindholm *et al.* (2011) (Figure 8). The forest residues were considered a residual product and no processes generating emissions before forwarding were included in the substitution factor. The energy substitution calculations are described in section *2.3.7 Energy recovery and substitution*.

Figure 8. System boundaries for assessment of emissions from wood chips produced from forest residues (green boxes) and energy substitution (grey boxes).

2.3.7 Energy recovery and substitution

The wood chips and waste wood materials (beverage carton, EcoFishBox™ and other pulp and paper products) were assumed to be incinerated in a combined heat and power plant for energy recovery. The electricity produced was assumed to substitute a Nordic marginal electricity mix, calculated based on dynamic energy modelling by Hagberg *et al.* (2017). The electricity mix consisted of hard coal, natural gas, wind power and solar power, and an average for the period 2020-2040 was calculated based on emissions data from Ecoinvent (Wernet *et al.*, 2016). Heat was assumed to substitute heat produced by natural gas. This gave a substitution emission factor of 0.66 kg CO_2-eq per kWh electricity and 0.11 kg CO_2-eq per kWh heat (Appendix 1). The influence of assumptions regarding the electricity mix was varied in a sensitivity analysis (see section *3.1.3 Sensitivity analysis*).

To calculate the total substitution effect for the end-of-life phase of waste wood products (LPB beverage carton, EcoFishBox™ and other pulp and paper products), the energy recovery of the replaced products (PET bottle and EPS box) was also considered. The total substitution effect was thus the difference between emissions from incinerating the wood and non-wood waste products, and the difference in energy output that could substitute different amounts of heat and power (Figure 9).

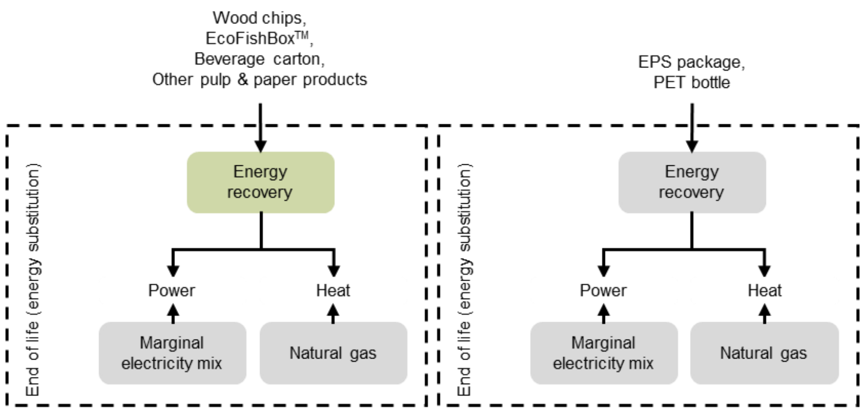

Figure 9. System boundaries for assessment of emissions from end-of-life management of wood products (green box) and replaced products and energy substitution (grey boxes).

The amounts of heat and power produced from wood chips and waste wood (LPB beverage carton, EcoFishBox™ and other pulp and paper products) and replaced products (PET bottle and EPS package) were calculated based on conversion efficiencies for a CHP plant (equipped with flue gas condensation for wood chip combustion) and the lower heating value (LHV) of fuels (Table 4).

Table 4. Lower heating value (LHV) and conversion efficiency of different products in combined heat and power production, including flue gas recovery for wood chips (for background data, see Appendix 1)

	LHV ($MJ\ kg^{-1}$)	Conversion efficiency (%)	
		Heat	Power
Wood chips	17.2[a]	75%	30%
Beverage carton	21.5[b]	55%	30%
EcoFishBox™	18.4[c]	55%	30%
PET bottle	25.1[b]	55%	30%
EPS package	39.6[c]	55%	30%
Other pulp and paper products	12.6[d]	55%	30%

[a]Appendix 1. [b]Calculated based on material composition and heating values as described in CEN 13431 (2004). [c]LCA consulting and Stora Enso (2018). [d]CEN 13431 (2004).

Fossil emissions from end-of-life incineration were calculated based on fossil carbon content (Table 5) and complete combustion was assumed, *i.e.* all fossil carbon was emitted as CO_2. The biogenic carbon emitted was accounted for separately (described in sections *2.4 Forest carbon stock* and *2.5 Harvested wood products*). A conversion factor of 44/12 was used for converting carbon to CO_2.

Table 5. Carbon content of different products (% per package or dry matter)

	Biogenic	Fossil	Total
Wood chips	50%	0%	50%
Beverage carton	29%	23%	52%
EcoFishBox™	38%	10%	49%
PET bottle	0%	63%	63%
EPS package	0%	92%	92%
Other paper and pulp products	41%	0%	41%

2.3.8 Summary of product emissions

Greenhouse gas emissions values for the wood products and replaced products assessed (Figure 10) were used in Equation 2 to calculate the substitution factors.

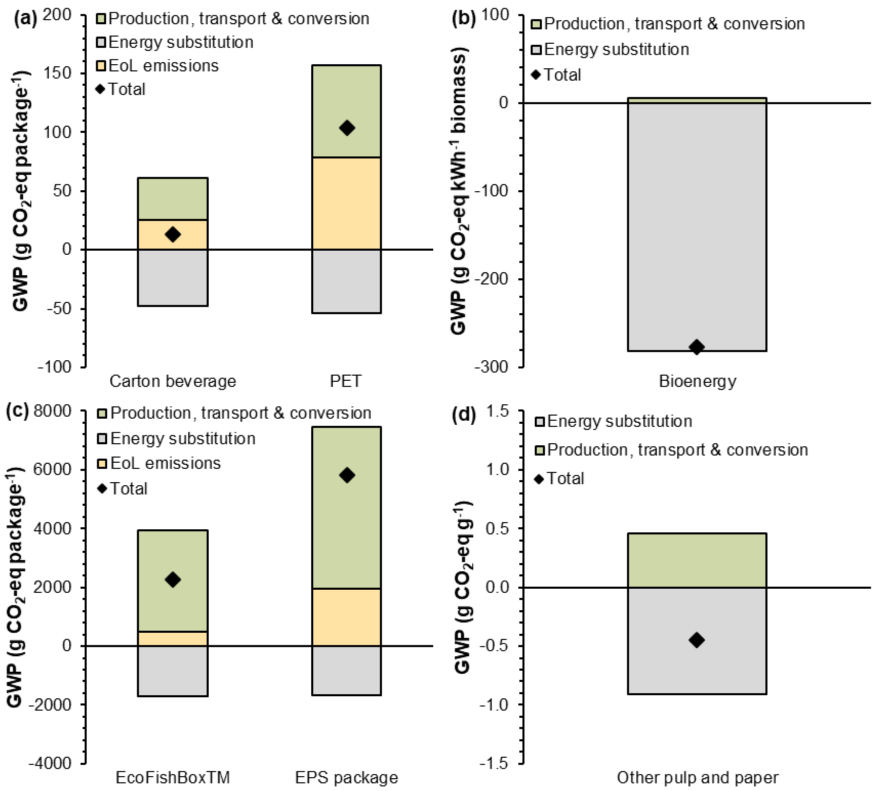

Figure 10. Global warming potential (GWP) for (a) liquid packaging board used for beverage carton and replaced PET bottle, (b) bioenergy, (c) corrugated board for EcoFishBox™ and replaced EPS package and (d) proxy for other pulp and paper products. Values exclude biogenic carbon fluxes from forest carbon stock changes and biogenic carbon emissions in end-of-life (EoL) management.

2.4 Forest carbon

2.4.1 Forest area

Forest carbon stock modelling included forest area owned or leased by Stora Enso in Sweden, Finland (via owning of 41% of Tornator Oyj), Brazil, Uruguay and China (Table 6). Different modelling approaches were applied for calculating carbon stock changes for conventional forestry in the Nordic countries (SIMO model, Heureka system and Q model) and eucalyptus plantations in Brazil, Uruguay and China (Yasso15 model). Forest carbon stock changes from purchased wood were not included in the assessment, while temporary carbon storage in harvested wood products was included for both Stora Enso's own wood and purchased wood.

Table 6. Forest area owned or leased by Stora Enso included in forest carbon stock modelling

Region	Area (ha)
Sweden	1 139 853[a]
Tornator, Finland	251 352[b]
Veracel, Brazil	46 766[c]
Montes del Plata, Uruguay	94 396[d]
Guangxi, China	73 999[e]
Total	1 606 366

[a]Productive forest land (growth more than 1 m^3 hectare and year) on mineral soils including voluntary set-asides and tree retention, total holdings 1.41 million ha. [b]41% of Tornator area, including productive forest land (67% mineral soils and 25% peat land) and unproductive forest land (3% shrub land and 5% waste land). [c]Productive area, 42% of total plantation area, 111 965 ha. [d]Productive area, 70% of total plantation area, 134 542 ha. [e]Productive area, 91% of total plantation area, 81048 ha.

Total biogenic carbon flux from the forest (ΔC_{forest}, Mg CO_2-eq yr^{-1}) was calculated as:

$$\Delta C_{forest} = \Delta C_{nordic} + \Delta C_{eucalyptus} \quad (9)$$

where ΔC_{nordic} is biogenic carbon flux from forest land in Finland and Sweden, and $\Delta C_{eucalyptus}$ is biogenic carbon flux from eucalyptus plantations in Brazil, Uruguay and China.

2.4.2 Swedish forest (Heureka and Q model)

The Heureka system coupled with the decomposition model Q was used for modelling biogenic carbon fluxes for the Swedish forests (Wikstrom *et al.*, 2011). Heureka simulates tree layer development using data on current forest conditions, site properties, management actions applied and tree-based functions for *e.g.* growth, ingrowth and mortality. Simulations are made of height development for individual trees in young growing stands (height <7 m) and basal area development in established stands (height >7 m) using different models (Fahlvik *et al.*, 2014). The simulations in the present study were initiated using inventory data on the current forest state and site conditions of the Swedish Stora Enso forest estate, and 2018 was set as the starting year for the simulations.

The scenario was simulated in the Heureka PlanWise application by first letting the programme generate a number of alternative management schedules over a 100-year period for each of the management units (stands) included. To limit execution times for the very large dataset, the analysis was made on a stratified sample of stands consisting of approximately 10% of the population. After generation of alternatives, the most appropriate alternative for each management unit was selected, using a linear programming optimisation model. The objective function was formulated to maximise net present value (NPV), *i.e.* the economic value of present and future forestry activities, calculated as predicted income minus the cost of future activities (such as thinning and clear-cutting with appropriate regeneration after harvest), assuming 2.5% interest rate. A number of constraints were included to limit the variation in harvest levels over time and to enforce annual allowable cut regulations in accordance with the Swedish Forestry Act. Costs and revenues associated with each simulated management activity were based on the Heureka functions for calculating costs and revenues (https://www.heurekaslu.org/help/en), using timber price lists and cost statistics supplied by Stora Enso as input parameters.

The process-based Q model, which is incorporated in the Heureka system, simulates decomposition of litter and soil organic matter by microorganisms (Rolff & Ågren, 1999). The model handles cohorts with different forest litter quality (*e.g.* stems, branches, needles, stumps, fine roots and coarse roots) separately and predicts how they decay over time. The model accounts for substrate quality, temperature, climate and different properties of the microbial community. For coarse woody litter, there is an invasion time before decomposers can access the substrate. During the decomposition process, carbon is lost as CO_2 to the atmosphere and the quality of the remaining substrates declines over time, leading to decreasing decomposition rate (Ågren *et al.*, 2007).

To account for the yearly carbon stock change, the output of the Heureka simulations was recalculated from the original five-year time step into one-year time steps using Matlab.

2.4.3 Finnish forest (SIMO model)

The SIMO (SIMulation and Optimization) model is an open programme for forest management planning originally developed at the University of Helsinki and currently maintained and developed by Simosol Oyj (can be downloaded from http://www.simo-project.org/). The SIMO model includes modules for describing forest growth, mortality and different forestry operations (Rasinmäki *et al.*, 2009). The growth and yield functions are based on those in Hynynen *et al.* (2002), which in turn were developed from data in the Finnish National Forest Inventory. Total aboveground and belowground biomass was estimated based on a biomass function described by Repola *et al.* (2007). The published growth models was calibrated for Tornator using their proprietary inventory data, since the calibrated models are better aligned with the actual growth of Tornator's forests.

Various alternative management schedules were applied for all management units (stands) in Stora Enso's associate company Tornator's forest estate in Finland. As in the Swedish forest simulations, the most appropriate schedule for each management unit was selected, using a linear programming optimisation model aiming to maximise NPV, assuming 3.5% interest rate.

SIMO uses Yasso for modelling soil carbon stock changes (described in section *2.4.4 Eucalyptus plantations (Yasso15 model)*). The SIMO model was used for modelling the forest carbon stock in biomass and soil for the years 2018-2118, using five-year time step. To account for the yearly carbon stock change, the output was recalculated into one-year time steps using Matlab.

2.4.4 Eucalyptus plantations (Yasso15 model)

For modelling soil carbon changes in eucalyptus plantations in Brazil, Uruguay and China, the Yasso15 model was used (Liski *et al.*, 2005) (an available R-version was used, which can be downloaded from https://en.ilmatieteenlaitos.fi/yasso). The yearly standing biomass stock of eucalyptus was calculated based on literature data and information from Stora Enso (Appendix 2). A yield of 77 Mg dry matter per hectare (excluding 13% bark, corresponding to around 140 m^3 sub) was assumed for all three locations, which resulted in differences in net primary productivity (NPP) and litter input since the rotation length in the three regions (Brazil, Uruguay, China) varied from 6 to 9 years.

The Yasso15 model divides the biomass litter into five compartments, called the AWENH compartments, depending on the chemical composition. These compartments consist of carbon compounds hydrolysable in acid, such as cellulose (A); extractives soluble in a polar solvent, such as water (W) (*e.g.* sugars), or in a non-polar solvent, such as ethanol (E) (*e.g.* waxes); compounds not soluble or hydrolysable, such as lignin (N), and humus (H) (Tuomi *et al.*, 2011). As the material decomposes, the carbon moves between the compartments or is released to the atmosphere as CO_2.

To run the model, information on climate, initial carbon content (in the form of an AWENH vector) and litter input during the time frame studied is needed. The litter is sorted based on diameter with an AWENH distribution for each size. The size groups used in the simulation in this study were foliage (non-woody material), fine roots, coarse roots, branches and bark, stems and stumps.

The most common previous land use was identified as grassland for all three regions. To determine the initial soil carbon content before the eucalyptus plantations were established, steady-state simulations were performed for each location. The model was then run for 1000 years with variables for grassland (initial soil carbon content, AWENH vector and litter input) and the humus fraction of the AWENH vector was adjusted to reach steady state (Appendix 2).

The output of the simulation was carbon stock development in one eucalyptus stand during 100 years. A landscape model was compiled in order to model the carbon stock increase for a whole landscape with varying age distribution. The landscape model consisted of identical eucalyptus stands, based on the output from the Yasso15 modelling, where the age of the plantations was evenly distributed. The landscape model also included carbon stored in aboveground and belowground biomass. Landscape-level data was updated based on forest area data for Eucalyptus plantations as of December 2020 (see Table 6).

2.5 Harvested wood products

2.5.1 Production volumes

Production volumes were obtained from Stora Enso and converted to mass of biogenic carbon using conversion factors of 0.5 Mg C Mg^{-1} dry matter for biomass, 0.10 Mg C MWh^{-1} for sold energy (based on lower heating value of 17.2 MJ kg^{-1} dry matter), 0.39 Mg C Mg^{-1} for paper, paperboard and recycled paper, 0.42 Mg C Mg^{-1} for liquid packaging board and 0.41 Mg C Mg^{-1} for market pulp (based on average for chemical wood pulp), and 0.25 Mg C m^{-3} for solid wood products (average for coniferous and non-coniferous sawnwood) (Rüter *et al.*, 2019) (Table 7).

Table 7. Production volume in mass of biogenic carbon in different products categories (from forest owned or leased by Stora Enso and purchased wood, virgin and recycled fibre) produced in year 2021 (source: communication by Johan Holm, January 2022)

	Million Mg C
Pulp and paper products	3.6
Solid wood products	1.4
Bioenergy	0.9
Total	5.9

Around 65% of the solid wood products were sawnwood and cross-laminated timber, while the rest were biocomposite and other processed products. Around

16% of the pulp and paper products from virgin fibre was liquid packaging board sold on the European market, around 8% was containerboard (excluding externally bought) and the largest share (76%) was other pulp and paper product categories (Table 8).

Table 8. Production volumes in mass of biogenic carbon in the pulp and paper products produced in year 2021 (source: communication by Johan Holm, January 2022)

	Million Mg C
Virgin fibre	2.8
Containerboard (excl. converted)	0.3
Containerboard (converted)	0.2[a]
Market pulp	0.5
Paper	0.6
Consumer board	1.3
Liquid packaging board Europe	0.4
Other consumer board products	0.8
Recycled fibre	0.8
Container board	0.4
Paper	0.4

[a]40% bought externally and not included in substitution calculation

2.5.2 Temporary carbon storage

At harvest, carbon stored in forest biomass is removed from the forest. However, this carbon is not released back to the atmosphere directly, but is instead stored in wood products for varying periods (Figure 11).

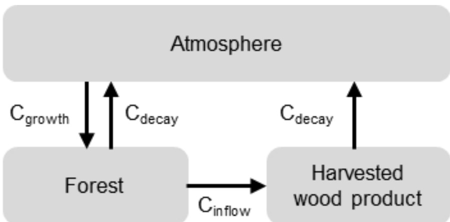

Figure 11. Biogenic carbon (C) fluxes in forest and harvested wood products.

Temporary carbon storage (Mg C) in harvested wood products (HWPs) from forests owned or leased by Stora Enso and purchased wood was calculated based on the methodology presented in Rüter *et al.* (2019):

$$C_{HWP}(t) = C_{HWP}(t-1) \cdot e^{-k} + \left[\frac{(1-e^{-k})}{k}\right] \cdot C_{inflow}(t) \quad (10)$$

where C_{HWP} is carbon stored in a specific wood product category, t is the studied year, C_{inflow} is added carbon from new wood products harvested during year t, and k is the decay constant of the specific wood product category, which describes the fraction of carbon lost to the atmosphere each year:

$$k = \frac{\ln(2)}{t_{1/2}} \quad (11)$$

The decay constant is calculated based on the half-life time ($t_{1/2}$) of the wood product category (Table 9). The half-life times only include single-stage cascading wood use (*i.e.* one product use and energy recovery), and the same half-life time was therefore used for both virgin and recycled paper fibres.

Table 9. Half-life time (yr), decay constant (yr^{-1}) and decay of carbon in harvested wood products from the previous year (C_{HWP}) and added carbon from new wood products (C_{inflow})

	Half-life time ($t_{1/2}$)	Decay constant (k)	Decay C_{HWP} (e^{-k})	Decay C_{inflow} ($(1-e^{-k})/k$)
Sawnwood	35[a]	0.020	0.98	0.99
Woodboard	25[a]	0.028	0.97	0.99
Paper and pulp	2[a]	0.347	0.71	0.85
Bioenergy	1[b]	0.693	0.50	0.72

[a]Rüter *et al.* (2019). [b]Assumed.

Four different categories of harvested wood products, where the carbon is released back to the atmosphere over different time frames, were considered in this study (Figure 12).

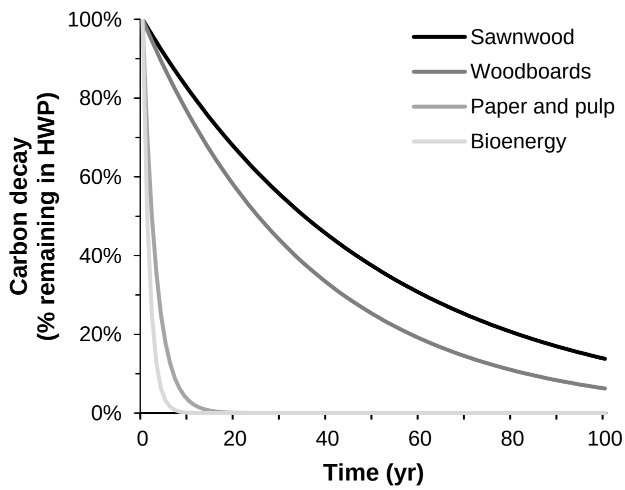

Figure 12. Temporary carbon storage in different harvested wood products (HWPs).

The biogenic carbon flux (Mg C yr^{-1}) from harvested wood products (ΔC_{HWP}) during year (t) was calculated as the difference between the studied year and the previous year:

$$\Delta C_{HWP}(t) = C_{HWP}(t-1) - C_{HWP}(t) \quad (12)$$

The initial harvested wood products stock, *i.e.* the starting value for the assessment, was calculated based on steady-state simulation with constant C_{inflow} using values for the year 2019 (Table 7) and a distribution between sawnwood and wood boards of 65% and 35%, respectively. Biogenic carbon fluxes from temporary carbon storage in wood products harvested for the assessed year was calculated as the average carbon storage during 100 years from the harvest year.

2.6 Value chain emissions

In its climate impact reporting, Stora Enso follows the greenhouse gas protocol (WRI & WBCSD, 2015) (Table 10). This protocol consist of three scopes, where scope 1 includes direct emissions from sources that are owned or controlled by the company; scope 2 includes indirect emissions from purchased electricity; and scope 3 includes other indirect emissions from sources that are not owned or controlled by the company. Scope 3 is voluntary and does not have to be reported by the company (WRI & WBCSD, 2015).

Table 10. Stora Enso's value chain emissions in 2021, in total and as reported under scope 1-3 of the greenhouse gas protocol (source: communication from Johan Holm, January 2022).

	Million Mg CO_2-eq
Scope 1	2.1
Scope 2	0.2
Scope 3	7.8
Total	10.2

For Stora Enso's climate reporting, emissions from operations that are owned or controlled to more than 50% by the company are included, while other operations are handled as suppliers. Since Stora Enso owns less than 50% of the Montes del Plata mill in Uruguay, and most of the market pulp produced is sold externally, these value chain emissions are excluded from the reporting.

3 Results and discussion

3.1 Substitution

3.1.1 Substitution factors

The substitution factors developed were divided into $SF_{production}$ (cradle-to-EoL) and SF_{EoL} (end-of-life emissions and energy substitution), to identify the part of the life cycle that gave the largest substitution (Figure 13). The highest total substitution factor (2.0 Mg C Mg^{-1} C) was found for the EcoFishBox^{TM}, followed by the LPB beverage carton (1.1 Mg C Mg^{-1} C). Excluding the Stora Enso value chain emissions gave higher substitution factors, of 2.8 Mg C Mg^{-1} C and 1.3 Mg C Mg^{-1} C for the EcoFishBox^{TM} and beverage carton, respectively. A review by Leskinen *et al.* (2018) reported average values within the range 1-1.5 Mg C Mg^{-1} C for the product category 'wood-based chemicals, furniture and packaging'.

For the product category other pulp and paper products, where no product substitution was identified, the proxy energy substitution factor (SF_{EoL}) was around 0.3 Mg C Mg^{-1} C when including the whole value chain (Figure 13a), and 0.6 Mg C Mg^{-1} C when excluding the value chain emissions of Stora Enso (Figure 13b). The total substitution effect was thus to a large degree counteracted by value chain emissions.

Bioenergy from wood chips substituted 0.7 Mg C Mg^{-1} C, which is in line with previous studies (Holmgren & Kolar, 2019). The substitution factors applied in substitution effect calculations for Stora Enso products are summarised in Table 11.

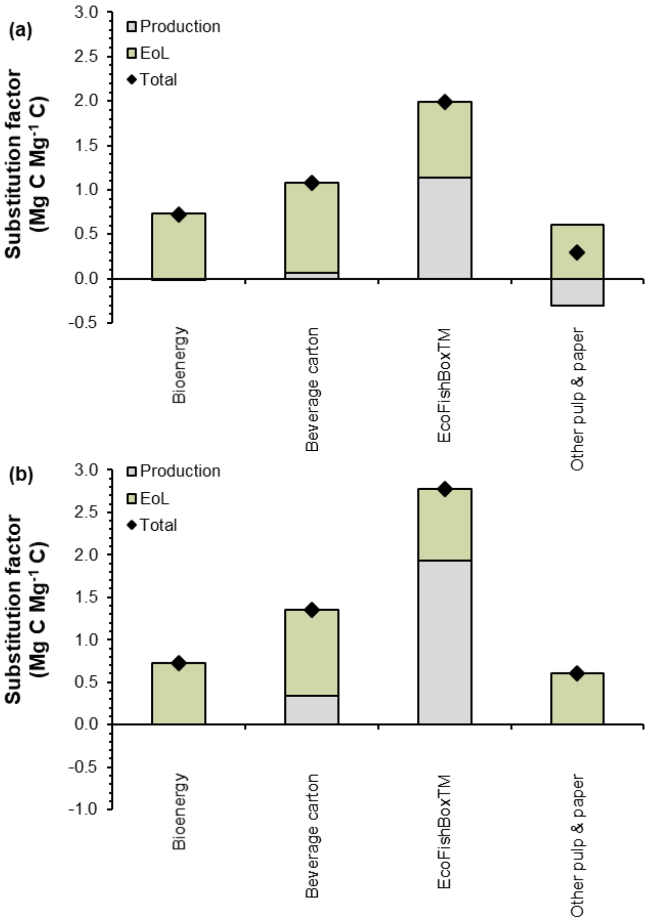

Figure 13. Substitution factors for the different wood-based products assessed (a) including Stora Enso's value chain emissions (VCE) and (b) without Stora Enso's VCE (EoL = end of life).

For solid wood products, a substitution factor of 1.5 Mg C Mg^{-1} C was applied, as it is currently used in Stora Enso's climate reporting. The value is based on a previous review by Holmgren and Kolar (2019). According to Leskinen *et al.* (2018), the average value for structural constructions (*e.g.* building materials and wood frames) is 1.3 Mg C Mg^{-1} C, and the average for non-structural constructions (*e.g.* windows and doors) is 1.6 Mg C Mg^{-1} C. However, those authors point out that there are large variations between studies and that the average values should be used with caution. Discrepancies may arise because the system boundaries for assessments can vary in terms of *e.g.* geographical location, time perspective, part of life cycle included and whether value chain emissions or biogenic carbon fluxes are included. In a meta-study of substitution factors for wood-based materials, Sathre and O'Connor (2010) found that most values were within the range 1.0-3.0 Mg C Mg^{-1} C, with a mean value of 2.1 Mg C Mg^{-1} C.

Table 11. Substitution factors (SFs) (Mg C Mg^{-1} C) applied in calculation of the substitution effect of Stora Enso's products, *i.e.* excluding value chain emissions to avoid double counting. SF_{EoL} includes emissions from end-of-life management (*i.e.* combustion) and energy substitution. Note: values should only be used when value chain emissions are reported separately

	$SF_{production}$	SF_{EoL}	SF_{total}
Bioenergy	0.0	0.7	0.7
Beverage carton	0.3	1.0	1.3
EcoFishBox™	1.9	0.8	2.8
Other pulp and paper products	0.0	0.6	0.6
Solid wood products[a]	-	-	1.5

[a]Based on previous studies.

3.1.2 Substitution effect

The overall substitution effect, following Equation 3 and Tables 7-8 and 11, was around 17.2 million Mg CO_2-eq (Figure 14) in 2021. Solid wood products had the highest substitution effect at company level, followed by other pulp and paper products, bioenergy and a beverage carton from liquid packaging board.

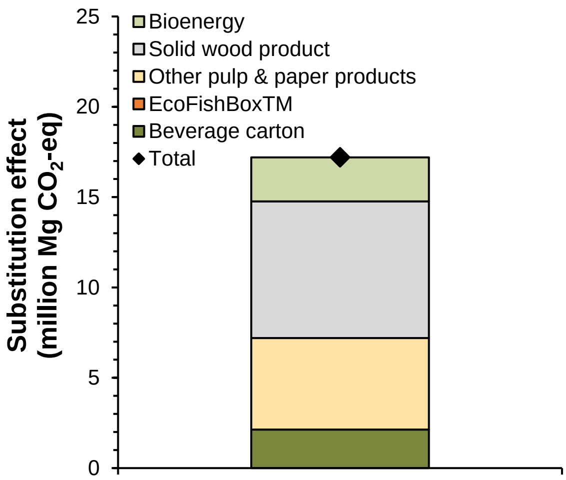

Figure 14. Substitution effect of Stora Enso's product portfolio in 2021. Note: no production of EcoFishBox™ assumed in the baseline scenario.

3.1.3 Sensitivity analysis

Several parameters were varied in the sensitivity analysis, to test the importance of modelling settings. Production figures in the sensitivity relate to production data for the year 2019. The first parameter varied was the replacement rate (R) of the beverage carton. In the baseline scenario, one beverage carton produced from liquid packaging board was assumed to replace 0.5 PET bottles (R = 0.5), in order to consider recycling of PET bottles into new PET bottles. To test the importance of this assumption, the replacement rate was changed so that one LPB beverage carton replaced 0.9 PET bottle (R = 0.9). This was based on that around 18% of the recycled PET bottles at European level were used as food bottles in 2018 (EUNOMIA, 2020), *i.e.* around 9% of PET bottles were collected and recycled into new PET bottles used for food products. The higher replacement rate increased the substitution factor from 1.1 to 2.3 Mg C Mg^{-1} C, which increased the overall substitution effect by 11% (Figure 15 and 17). The remaining share of the recycled PET can however be used for other blow-moulding non-food products, sheets, fibre, strapping and other PET products, which was not considered in this assessment. The sensitivity analysis shows that assumptions made regarding recycling and cascading wood use affects the results.

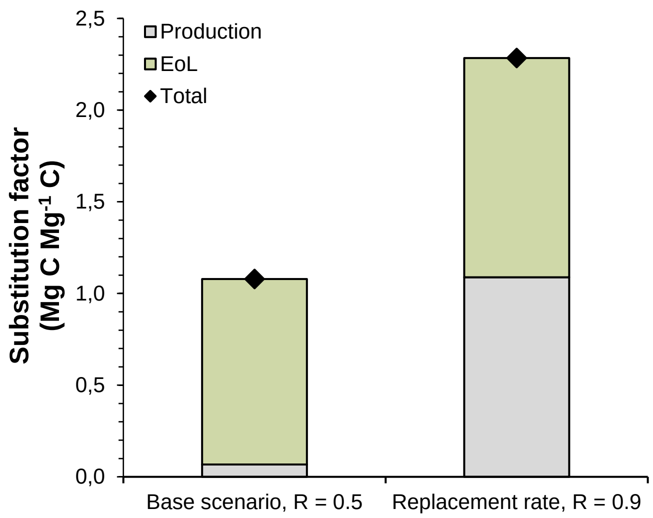

Figure 15. Sensitivity analysis of different replacement rates (R) of a liquid packaging board beverage carton replacing a PET bottle (EoL = end of life).

The second parameter varied in the sensitivity analysis was energy substitution. The marginal electricity mix assumed in the baseline scenario was based on Hagberg *et al.* (2017), where an average was calculated for the period 2020-2040. The electricity mix mainly consisted of hard coal, wind power and natural gas (Appendix 1). To test the importance of the selected electricity mix, a less greenhouse gas-intensive marginal electricity (with equal shares of solar power, wind power and natural gas) was assumed, which had a climate impact of 0.15 kg CO_2-eq kWh^{-1} electricity.

The less greenhouse gas-intensive electricity mix had a large impact on the substitution factor of bioenergy, the LPB beverage carton and energy substitution of other pulp and paper products (Figure 16). The EcoFishBox™ was impacted to a low degree, since the amount of energy recovered for the two types of fish boxes compared (EcoFishBox™ and EPS box) was of similar magnitude, and thus the effect of the substituted energy was small. The energy substitution by other pulp and paper products decreased from around 0.6 to 0.3 Mg C Mg^{-1} C on excluding the value chain emissions, while the total substitution factor was negative, *i.e.* gave no climate benefit, when the less greenhouse gas-intensive electricity mix was applied (Figure 16).

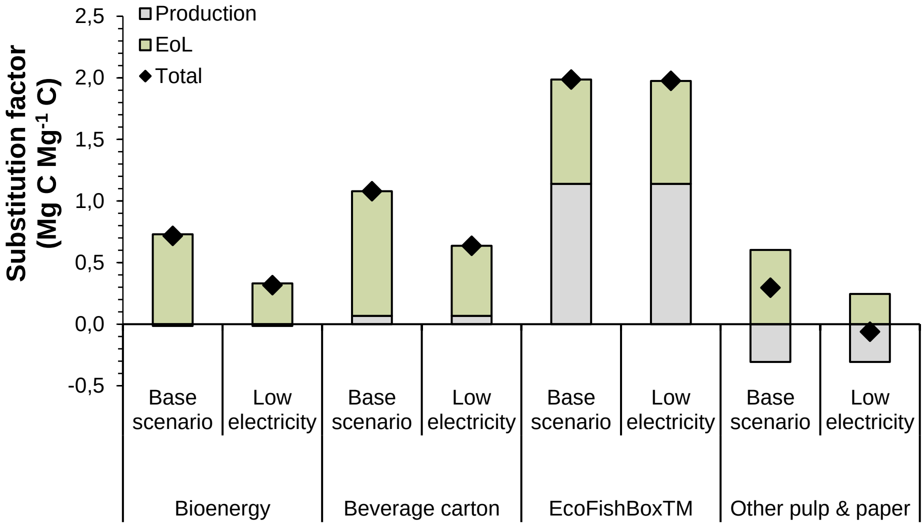

Figure 16. Sensitivity analysis of marginal electricity mix used for energy substitution calculations, showing total substitution effect (*i.e.* including value chain emissions).

The overall impact on the total substitution effect of a less greenhouse gas-intensive electricity mix was a decrease of around 30%, where bioenergy substitution had the highest impact (Figure 17). This shows that the substitution effect is influenced by changes in the energy system and indicates that future replacement of fossil energy with other renewables may decrease the climate benefit of bio-based energy.

The potential substitution effect of the EcoFishBox™ was also assessed. According to Material Economics (2018), the potential substitution of plastic packaging (film, netting, labels and foam) in Europe is 0.3 million Mg, which corresponds to around 0.7 million Mg EcoFishBox™ units substituting EPS boxes (about 0.6 million Mg corrugated board), which is of the same magnitude as the current corrugated board production from virgin fibre. If all corrugated board were to be used for EcoFishBox™ production, the substitution effect would increase by 11%. If 50% of the potential substitution of EPS boxes were to be achieved (and 50% for energy recovery only), the total substitution effect would be 5% higher (Figure 17).

It should also be noted that the substitution effect of solid wood products was not varied in the sensitivity analysis, since a substitution factor based on previous studies was used. However, *e.g.* a change in marginal electricity mix would also affect the substitution effect of solid wood products.

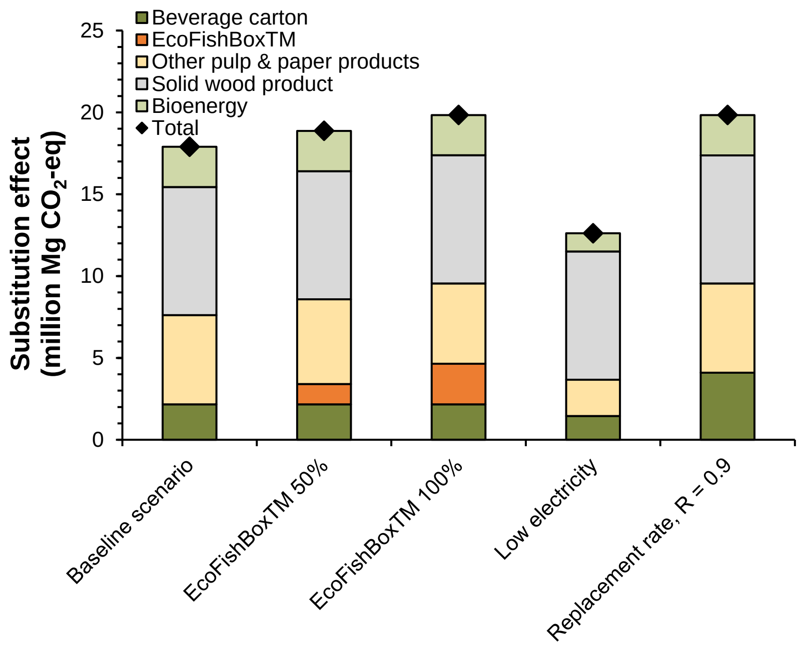

Figure 17. Sensitivity analysis of the total substitution effect of varying the extent (50%, 100%) of EcoFishBox^{TM} replacing EPS boxes, use of a lower fossil-intensive marginal electricity mix and higher replacement rates (R = 0.9 instead of 0.5) of a liquid packaging board beverage carton replacing a PET bottle. Note: the substitution factor for solid wood products was constant and not varied in the sensitivity analysis.

3.2 Biogenic carbon flux

3.2.1 Forest carbon stock

The average forest carbon stock when including the total area owned or leased by Stora Enso was highest in the Nordic countries. However, considering the difference in forest area in the different locations, the average carbon stock per hectare was within the same range of magnitude in all countries except Finland, where forest soil had a higher carbon content (Figure 18). The Finnish soil carbon stock was higher than at the other locations because a higher share (25%) of peatland and unproductive forest land (8%) was included in the total area. The carbon stock in peatland remains stable in SIMO simulations, which means that even though the carbon stock in Finnish soils was high, the yearly biogenic carbon flux was comparable to that at the other locations. In total, the forests owned or leased by Stora Enso store on average around 230 million Mg C (corresponding to around 840 million Mg CO_2).

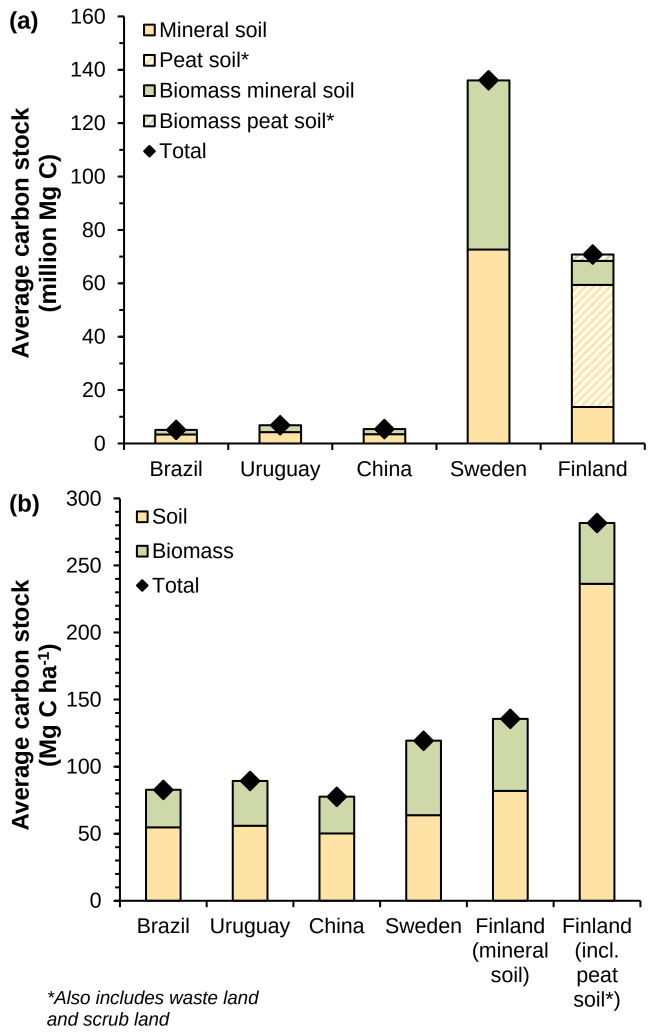

Figure 18. Carbon stock in forests owned or leased by Stora Enso in different countries (based on 100-year projections). Average yearly carbon stock in (a) forest biomass and soil per country (Brazil, 46 766 ha, Uruguay, 94 396 ha, China, 73 999 ha, Sweden, 1 139 853 ha, Finland, 251 352 ha) and (b) per hectare of forest biomass and soil in each country. Finnish forest is divided for mineral soils (67% of forest area) and peat land (25% of forest area), which also includes shrub land (3% of forest area) and waste land (5% of forest area). Note: scale differences.

Average annual biomass outtake per hectare was found to be larger in the eucalyptus plantations than the Nordic forests (Figure 19). Net primary production and rotation length of the eucalyptus plantations varied with geographical location, which affected the yearly litter input to the soil and consequently the change in carbon stock.

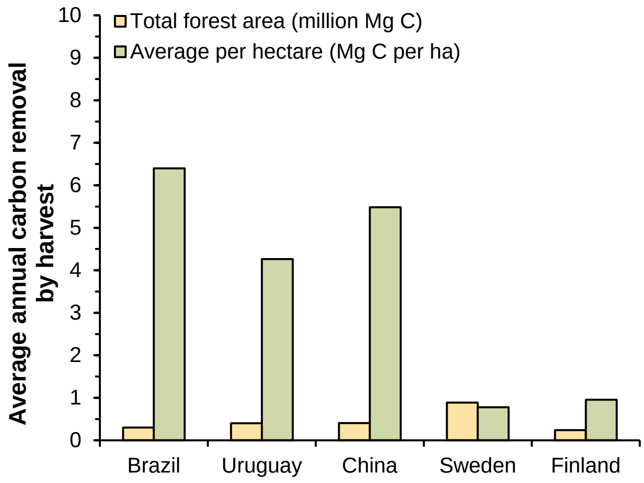

Figure 19. Average annual carbon removal by harvest of forest owned or leased by Stora Enso in different countries (based on 100-year projections).

For all three regions (Brazil, Uruguay, China), the highest carbon stock increase occurred in the beginning of the time frame studied, *i.e.* when the eucalyptus plantation was established on grassland. This was because the new plantations had higher yearly carbon input to the soil through litter than the previous land use. Over time, a new balance between carbon input from litter and decomposition was reached. For the Nordic forests, the carbon stock increased over time, with the Swedish forest having the highest total increase (Figure 20).

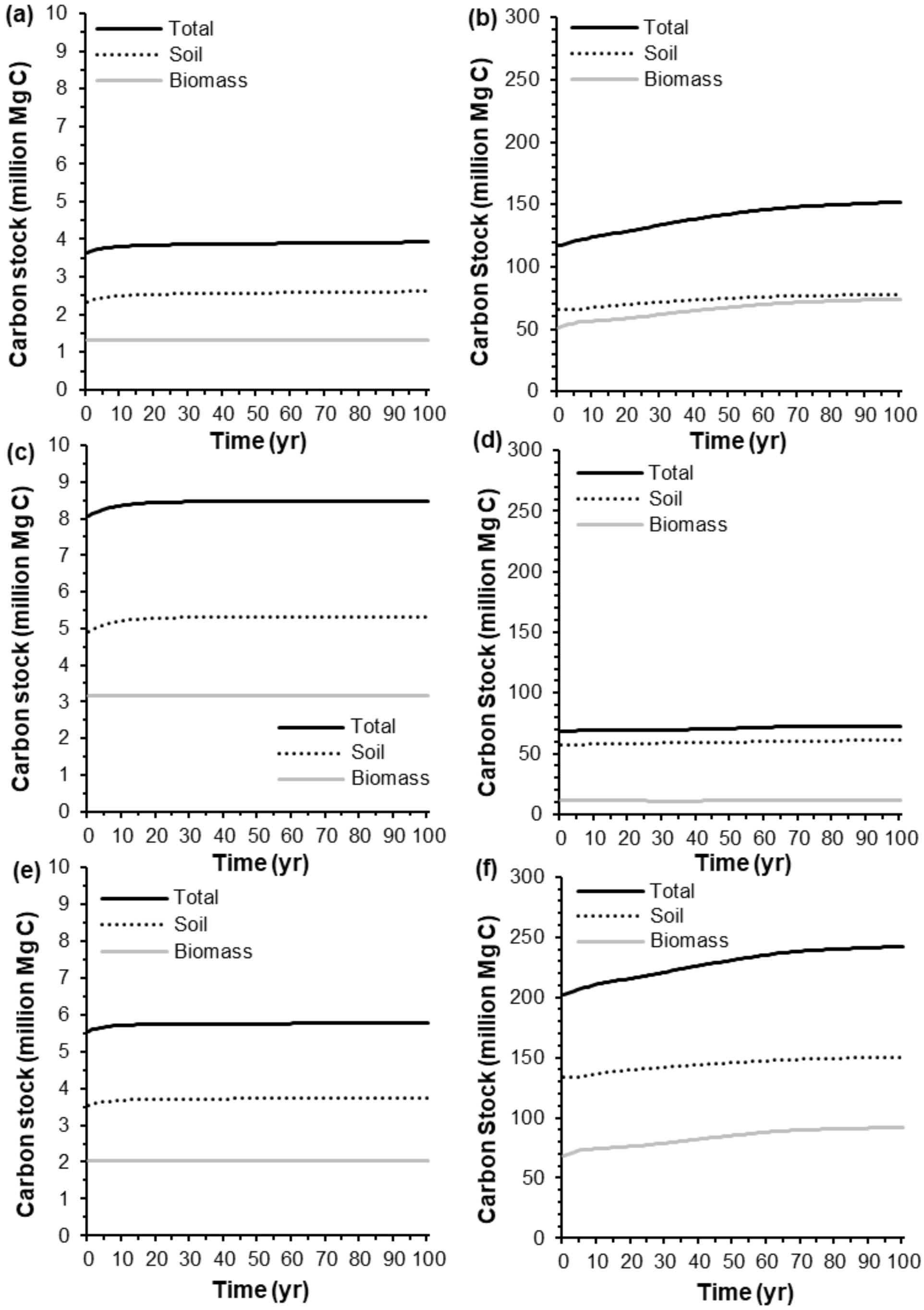

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Figure 20. Carbon stock in forest land owned or leased by Stora Enso in (a) Brazil (46 766 ha), (b) Sweden (1 139 853 ha), (c) Uruguay (94 396 ha), (d) Finland (251 352 ha, including 25% peat land and 8% unproductive forest), (e) China (73 999 ha) and (f) total forest area in all regions (1 606 366 ha). Note: scale differences.

The yearly carbon stock change varied over time, and thus the carbon sequestration effect varied depending on the time perspective applied in the assessment (*i.e.* change for a specific year or average over a number of years). In the annual climate impact reporting at company level in Stora Enso, an average carbon flux calculated for a 100-year period was applied (Figure 21).

The largest total carbon increase was found for the Swedish forest, due to the larger total forest area but also due to greater carbon uptake per hectare and year. The average annual carbon flux for all forest land owned or leased by Stora Enso was -1.5 million Mg CO_2 yr^{-1} (corresponding to an average of -0.9 Mg CO_2 ha^{-1} and yr^{-1}), *i.e.* net removal of CO_2 from the atmosphere. According to the Swedish Environmental Protection Agency (EPA), net removal in forest land in Sweden was -44.4 million Mg CO_2 in 2017 (Swedish EPA, 2019), which is around -1.6 Mg CO_2 per hectare forest land (also including unproductive forest land). Only considering productive forest lowers the net removal to about -0.9 Mg CO_2 per hectare (Government Offices of Sweden, 2019), *i.e.* the same value as for all forest land owned or leased by Stora Enso.

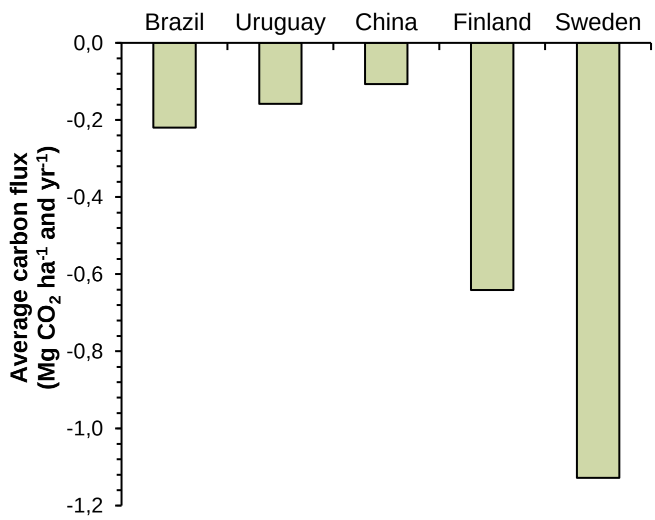

Figure 21. Average annual carbon stock change calculated for a 100-year time period for the different countries in which Stora Enso owns or leases forest. Negative values indicate uptake, *i.e.* removal of CO_2 from the atmosphere.

3.2.2 Harvested wood products

The carbon inflow in harvested wood products during the assessment year, 2021, was 5.9 million Mg C. Of this, 5.1 million Mg C remained after the first-year decay (of which 1.4 million Mg C was in long-lived wood products, *i.e.* sawnwood and woodboard) (Figure 22). After 100 years, 0.2 million Mg C remained stored in harvested wood products, and the annual average carbon stock was 0.7 million Mg C yr^{-1} (corresponding to 2.5 million Mg CO_2-eq yr^{-1}).

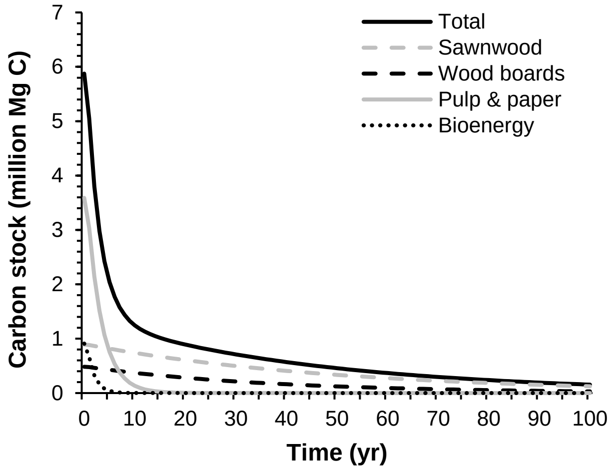

Figure 22. Carbon storage in harvested wood products produced by Stora Enso during the year 2021 (from forest owned or leased by Stora Enso and purchased wood, virgin and recycled fibres).

The total carbon stock in harvested wood products (including the initial HWP carbon pool from the steady-state simulation) was around 74 million Mg C, with most of this carbon (~84%) stored in sawnwood and woodboard (Figure 23).

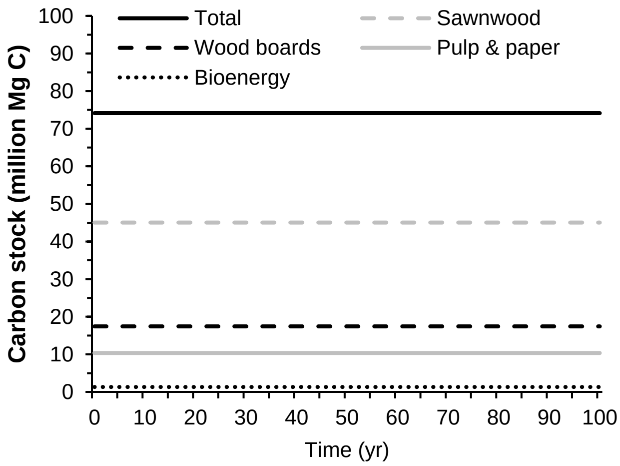

Figure 23. Carbon storage in harvested wood products at constant production volumes.

The CO_2 flux from the harvested wood products pool applied in the climate impact calculation was -2.5 million Mg CO_2 yr^{-1}, *i.e.* the average amount of CO_2 kept away from the atmosphere each year from one-year harvest.

3.2.3 Influence of time perspective

For the yearly climate reporting, the results from the dynamic forest carbon modelling were allocated to a one-year flux, which can be done using different approaches. In the baseline scenario, the average annual flux from the forest was calculated based on the 100-year simulation, while the temporary carbon flux was calculated as the average annual storage during 100 years. To test the influence of this setting, a sensitivity analysis was performed where different time perspectives were applied (Figure 24).

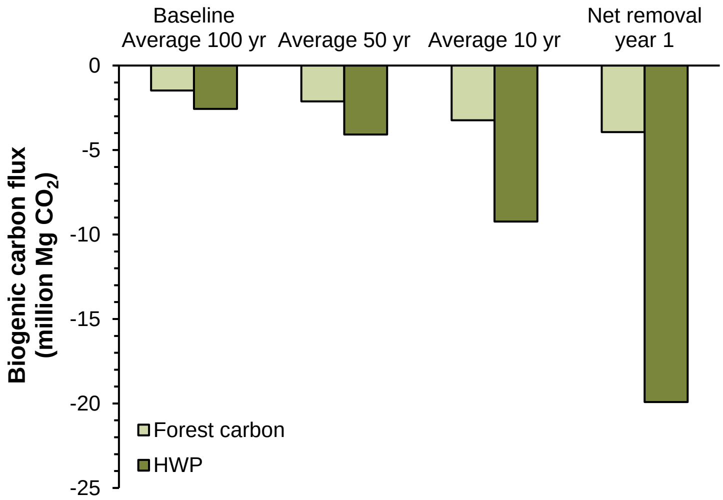

Figure 24. Biogenic carbon flux from forest and temporary carbon storage in harvested wood products (HWPs) calculated with different time perspectives.

A shorter time perspective resulted in higher biogenic carbon uptake, where temporary carbon storage in harvested wood products had the largest effect. This was due to the strong influence of carbon stored in short-lived products. For forest carbon the time frame also had an impact, with a 10-year perspective increasing the biogenic carbon uptake by around 120%. This was due to the higher forest growth in the beginning of the study period (see Figure 20).

3.3 Climate impact

The overall climate effect of Stora Enso when including value chain emissions, forest carbon stock changes, temporary carbon storage in harvested wood products and avoided emissions from substitution was -11.0 million Mg CO_2-eq, *i.e.* it resulted in a climate benefit (Figure 25). The main climate benefit derived from the substitution effect (removal of 17.2 million Mg CO_2-eq), and excluding this effect resulted in a climate impact of 6.2 million Mg CO_2-eq. Net annual CO_2 removal in forest land and harvested wood products (3.9 million Mg CO2-eq yr-1) counteracted about 40% of the value chain emissions (10.2 million Mg CO2-eq yr-1).

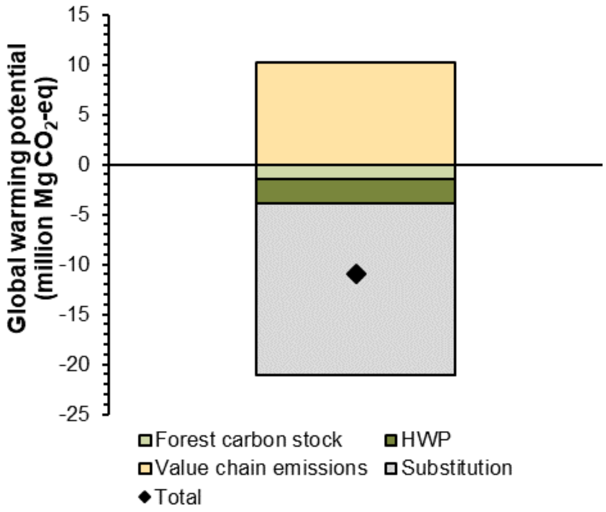

Figure 25. Global warming potential of Stora Enso during the year 2021 (HWP = harvested wood products). A negative value indicates a climate benefit, *i.e.* net removal of CO_2-eq from the atmosphere.

3.4 General discussion

The climate effects of forestry and wood-based products is often debated, and one explanation for contradictory viewpoints may be different assumptions regarding system boundaries. In this assessment, a system perspective was applied, where value chain emissions from forestry, biogenic carbon fluxes from forests and harvested wood products, and the benefit from substitution were considered. The study added to previous research by developing several new substitution factors for pulp and paper products and by performing dynamic modelling of forest carbon stock changes and temporary carbon storage in harvested wood products.

The results showed that the climate benefit of a forestry company is highly dependent on the potential substitution effect, *i.e.* the replacement of more greenhouse gas-intensive products. Identifying product substitution options is complex, however. For the majority of the pulp and paper products produced by the forestry company examined in the present assessment (Stora Enso), no product substitution was identified, since the product category comprised well-established products that are already market leaders. However, it is still possible to make improvements by including prospective products that have the potential for substitution effects in the future. Some previous studies have considered product substitution from pulp, *e.g.* reading on a tablet instead of paper, different types of textiles replaced by dissolving pulp or substitution effects from by-products like lignin, tall oil or methanol replacing fossil-based chemicals or fuels (Hermansson *et al.*, 2020; Peñaloza *et al.*, 2018; Sandin *et al.*, 2015).

A difficulty with calculating product substitution effects for forestry products is cascading wood use, where wood fibres are recycled into different products. There is complexity in identifying the cascading wood use chains and also in recycling of substituted products and allocating the potential burden or benefit between different life cycle stages. In this work, the energy substitution was allocated to the virgin wood fibres, to avoid double counting of energy substitution at end-of-life.

The question of allocation also arises in biogenic carbon accounting. In this study, biogenic carbon fluxes in forest land owned or leased by Stora Enso were considered, while fluxes in harvested wood products were also included as temporary carbon storage in purchased wood (both virgin and recycled fibres). Stora Enso purchases about 70% of their wood supply, and accounting the biogenic carbon of this forest land would give an additional climate effect (estimated to about -5.0 million Mg CO_2, Appendix 3). Depending on the aim and applied perspective, in this case a company perspective, the system boundaries can be set differently. This also applies for the market pulp that is sold externally, and thus outside the system boundaries of the substitution calculations. Considering this market pulp would give an additional climate benefit of about -0.5 million Mg CO_2-eq from energy substitution.

There are several other methodological choices in biogenic carbon accounting, concerning: (1) choice of time frame for the assessment (short- or long-term perspective); (2) backward- or forward-looking perspective; (3) static or dynamic modelling; (4) choice of reference land use; and (5) system boundaries (forest carbon stock and/or temporary carbon storage in wood products) (Agostini *et al.*, 2020; Albers *et al.*, 2020; Garcia *et al.*, 2020; Lueddeckens *et al.*, 2020; Soimakallio *et al.*, 2015; Helin *et al.*, 2013). In this work, biogenic carbon in both the forest and harvested wood products was considered. The system boundaries for the forest land was set to productive forest (except for the Finnish forest, which included about 8% unproductive forest). Considering all unproductive forest land owned or leased by Stora Enso would provide a broader picture of the company's total carbon flux.

A dynamic modelling approach of the biogenic carbon was applied for the life cycle inventory, *i.e.* the yearly carbon fluxes over time were calculated. However, since the aim was to assess the climate impact for one year, expressed in CO_2-eq, the dynamic fluxes over time were allocated to a single year by calculating an average carbon flux, which required selecting a time horizon. Sensitivity analysis showed that the choice of time horizon affected the biogenic carbon flux. To avoid this problem, a climate metric that considers the timing of greenhouse gas fluxes and displays the impact over time could be used, *i.e.* a time-dependent climate metric that displays both the short- and long-term impact (Levasseur *et al.*, 2016; Ericsson *et al.*, 2013).

The time aspect is also important for substitution calculations, since both wood-based products and substituted products may develop over time. The demand for wood-based products may change under a future bioeconomy, with new emerging biorefinery technologies (Antikainen *et al.*, 2017) and changes in demand for forest biomass (Bryngemark, 2019; Hurmekoski *et al.*, 2018; Börjesson *et al.*, 2017).

Lastly, it is important to distinguish between an absolute cooling climate effect due to substitution, *i.e.* net removal of emissions, and an avoided warming climate effect due to lower emissions compared with an alternative product, even though absolute emissions may increase. To meet global climate targets, it is crucial to reduce current emission levels and avoid increasing overall consumption.

4 Conclusions

The climate effects of the global renewable material company Stora Enso was estimated to be net removal of -11.0 million Mg CO_2-eq yr^{-1} (*i.e.* a climate benefit) when considering value chain emissions, biogenic carbon fluxes from forest land and harvested wood products, and avoided emissions from substitution. The net removal from biogenic carbon counteracted around 40% of the value chain emissions, while the largest climate benefit was due to the substitution of more greenhouse gas-intensive products (removal of 17.2 million Mg CO_2-eq).

Substitution factors developed for pulp and paper products in Hammar et al. (2020) were within the range 0.3-2.0 Mg C Mg^{-1} C (0.6-2.8 Mg C Mg^{-1} C excluding Stora Enso's value chain emissions). Assumptions regarding recycling and substituted electricity are quite influential, though. There are future possibilities for improvements by studying more pulp-based products, especially new emerging technologies, and methodological developments in recycling and substitution from cascading wood use.

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Appendix 1 – Substitution factors

Table A1. Heating values

	MJ kg^{-1}	Reference
LPB	12.6	CEN 13431 (2004)
Corrugated board	14.0	LCA consulting and Stora Enso (2018)
LDPE incl. LLDPE	43.0	CEN 13431 (2004)
Aluminium	31.0	CEN 13431 (2004)
HDPE	43.0	CEN 13431 (2004)
PP	44.0	CEN 13431 (2004)
PET	22.0	CEN 13431 (2004)
Carbon black	27.2	Assumed equal to that for hard coal in Swedish Energy Agency (2017)

A higher heating value (HHV) of 20.8 MJ kg^{-1} for wood chips (Nilsson *et al.*, 2012) was used for calculating the lower heating value (LHV) adjusted for a moisture content (MC) of 45% of wet mass and ash content (AC) of 1.5% of dry mass:

$$LHV_{MC} = (HHV - 2.45 \cdot 0.09 \cdot H_2) \cdot \left(1 - \frac{AC}{100}\right) - 2.45 \cdot \frac{MC}{100-MC} \quad \text{(MJ kg}^{-1}\text{ DM) (A1)}$$

where LHV_{MC} is the theoretical heat gain from wood chips excluding water condensation heat, 2.45 is the latent heat of water vaporisation at 20°C (MJ kg^{-1}), 0.09 represents one part hydrogen and eight parts oxygen in water, and H_2 is the hydrogen content (6% assumed) (Lehtikangas, 1999).

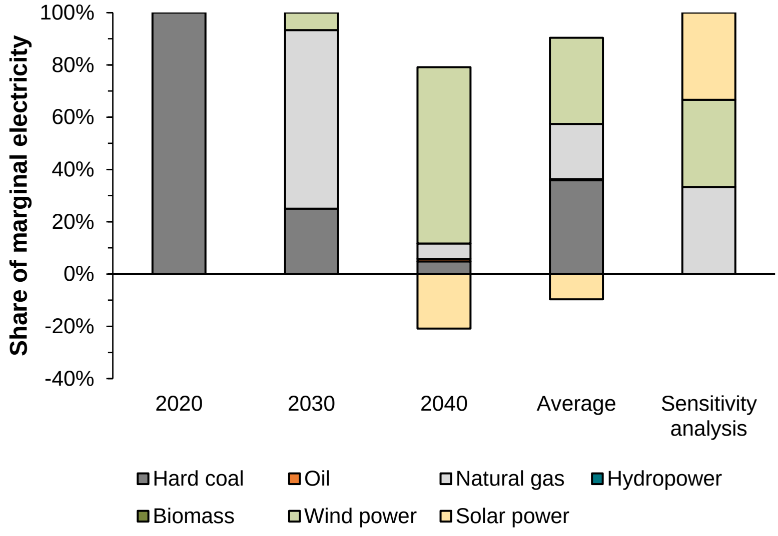

Figure A1. Marginal electricity mix used in the baseline scenario (average), calculated based on Hagberg *et al.* (2017), and changes tested in a sensitivity analysis. A positive value indicates increased production with increased electricity demand and a negative value indicates reduced production with increased power demand.

Table A2. Emission factors applied in energy substitution calculations

Fuel	kg CO_2-eq kWh^{-1} power
Hard coal	1.27[a]
Oil	0.83[a]
Natural gas	0.36[a]
Hydropower	0.05[a]
Wind power	0.01[a]
Solar power	0.08[a]
Marginal electricity mix	
Average	0.66[b]
Sensitivity analysis	0.15[b]

[a]Wernet *et al.* (2016), [b]Calculated based on emissions factors and share from Figure A1.

Appendix 2 – Yasso15

Table A3. Input data for Veracel, Brazil

Variable	Input value	Units	Comment
Mean temperature	23.06	°C	(Lourenco & Ferreira, Stora Enso)
Temperature amplitude	2.0	°C	Calculated from: Mean in warmest month = 24.9 °C (Lourenco & Ferreira, Stora Enso) and mean in coldest month = 20.9 °C (Lourenco & Ferreira, Stora Enso)
Precipitation	1357	mm	Calculated by summarising mean monthly precipitation from 15 years (Lourenco & Ferreira, Stora Enso).
InitialCPool	(2.4, 0.26, 0.51, 12.93, 35.15)	Mg C ha^{-1} as AWENH vector	Calculated in R-script from: Initial mass C, 51.32 Mg C ha^{-1} and initial AWENH distribution = (0.047; 0.005; 0.010; 0.252; 0.685), both from steady state simulation (Table A5).
LitterInput *(mass vectors, distributed between the AWENH compartments in R-script)*	Branches, bark, coarse roots: (0, 0, 0, 0, 0, 11.81) Stumps: (0, 0, 0, 0, 0, 4.46) Foliage: (1.04, 0.77, 0.5, 0.62, 0.74, 2.56) Fine roots: (0.56, 1.41, 0.85, 0.85, 1.71, 2.5)	Mg C ha^{-1} $yr^{-}1$ as a vector with an element for each year in the harvest cycle.	Calculated from biomass stock (Lourenco & Ferreira, Stora Enso) with carbon content 0.5 (Paula Susila, Stora Enso), turnover rate 0.5 for foliage (Lemma *et al.*, 2007) and 0.52 for fine roots (Gill & Jackson, 2000), part bark of trunk 13% (Paula Susila, Stora Enso) and the assumption that only foliage and fine roots fall as litter before harvest. At harvest, everything but the stems are left on the ground.
LitterInput *(AWENH vectors for distribution of mass in R-script)*	Branches, bark, coarse roots: (0.65, 0.015, 0.015, 0.32, 0) Stumps: (0.75, 0.015, 0.015, 0.22, 0) Foliage: (0.31, 0.165, 0.165, 0.36, 0) Fine roots: (0.51, 0.05, 0.05, 0.39, 0)	Distribution between the AWENH fractions for each litter size as a vector.	Branches, bark, coarse roots (Ravina da Silva, 2014; Lemma *et al.*, 2007) Stumps (Santos *et al.*, 2016; Ravina da Silva, 2014) Foliage (Lemma *et al.*, 2007) Fine roots (Lemma *et al.*, 2007) All values for the W and E compartments are calculated from the value for extractives

			split in two, since extractives includes both W and E.
WoodySize	Branches, bark, coarse roots: 7.1 Stumps: 21.9 Foliage: 0 Fine roots: 0.2	cm	Branches, bark, coarse roots: mean diameter of residues at harvest (Lourenco & Ferreira, Stora Enso). Stumps: mean diameter of stumps at harvest (Lourenco & Ferreira, Stora Enso). Foliage: Non-woody material is set to 0 (Yasso code). Fine roots (Lemma *et al.*, 2007)

Table A4. Input data for Guangxi, China

Variable	Input value	Units	Comment
Mean temperature	22.52	°C	(Brick Chen, Stora Enso)
Temperature amplitude	8.05	°C	Calculated in R-script from: Mean in warmest month = 30.2 °C (Brick Chen, Stora Enso) and mean in coldest month = 14.1 °C (Brick Chen, Stora Enso)
Precipitation	1838	mm	(Brick Chen, Stora Enso)
InitialCPool	(2.21, 0.20, 0.50, 11.63, 35.59)	Mg C ha^{-1} as AWENH vector	Calculated in R-script from: Initial mass C, 50.12 Mg C ha^{-1} and initial AWENH distribution = (0.044; 0.004; 0.010; 0.232; 0.710), both from steady state simulation (Table A5).
LitterInput *(mass vectors, distributed between the AWENH compartments in R-script)*	Branches, bark, coarse roots: (0, 0, 0, 0, 0, 0, 11.81) Stumps: (0, 0, 0, 0, 0, 0, 4.46) Foliage: (1.04, 0.86, 0.68, 0.5, 0.62, 0.74, 2.56) Fine roots: (0.56, 0.66, 0.75, 0.85, 0.85, 0.85, 2.5)	Mg C ha^{-1} yr^{-1} as a vector with an element for each year in the harvest cycle.	Calculated from NPP (Lourenco & Ferreira, Stora Enso) with carbon content 0.5 (Paula Susila, Stora Enso), turnover rate 0.5 for foliage (Lemma *et al.*, 2007) and 0.52 for fine roots (Gill & Jackson, 2000), part bark of trunk 13% (Paula Susila, Stora Enso) and the assumption that only foliage and fine roots fall as litter before harvest. At harvest, everything but the stems are left at the ground.
LitterInput *(AWENH vectors for distribution of*	Branches, bark, coarse roots: (0.65, 0.015, 0.015, 0.32, 0)	Distribution between the AWENH fractions for	Branches, bark, coarse roots (Ravina da Silva, 2014; Lemma *et al.*, 2007)

mass in R-script)	Stumps: (0.75, 0.015, 0.015, 0.22, 0) Foliage: (0.31, 0.165, 0.165, 0.36, 0) Fine roots: (0.51, 0.05, 0.05, 0.39, 0)	each litter size as a vector.	Stumps (Ravina da Silva, 2014) Foliage (Lemma *et al.*, 2007) Fine roots (Lemma *et al.*, 2007) All values for the W and E compartments are calculated from the value for extractives split in two, since extractives includes both W and E.
WoodySize	Branches, bark, coarse roots, tops: 5.1 Stumps: 15.6 Foliage: 0 Fine roots: 0.2	cm	Branches, bark, coarse roots, tops: mean of tops = 6 cm and branches 4.2 cm (Brick Chen, Stora Enso) Stumps (Brick Chen, Stora Enso) Foliage: Non-woody material is set to 0 (Yasso code). Fine roots (Lemma *et al.*, 2007)

Table A5. Input data for Montes del Plata, Uruguay

Variable	Input value	Units	Calculation, comment and reference
Mean temperature	17.5	°C	(Magdalena Pelufo, Stora Enso)
Temperature amplitude	5.9	°C	Calculated in R-script from: Mean in warmest month = 25.1 °C and mean in coldest month = 13.3 °C
Precipitation	1325	mm	Calculated average from interval 1100-1550 mm (Magdalena Pelufo, Stora Enso)
InitialCPool	(3.59, 0.38, 0.49, 11.75, 38.13)	Mg C ha^{-1} as AWENH vector	Calculated in R-script from: Initial mass C, 54.39 Mg C ha^{-1} and initial AWENH distribution = (0.066; 0.007; 0.009; 0.216; 0.701), both from steady state simulation (Table A5).
LitterInput *(mass vectors, later distributed between the AWENH compartments in R-script)*	Branches, bark, coarse roots: (0, 0, 0, 0, 0, 0, 0, 0, 11.81) Stumps: (0, 0, 0, 0, 0, 0, 0, 0, 4.46)	Mg C ha^{-1} yr-1 as a vector with an element for each year in the	Calculated from biomass stock (Lourenco & Ferreira, Stora Enso) with carbon content 0.5 (Paula Susila, Stora Enso), turnover rate 0.5 for foliage (Lemma *et al.*,

	Foliage: (1.04, 0.86, 0.68, 0.50, 0.62, 0.74, 0.78, 0.81, 2.56) Fine roots: (0.56, 0.66, 0.75, 0.85, 0.85, 0.85, 0.85, 0.85, 2.5)	harvest cycle.	2007) and 0.52 for fine roots (Gill & Jackson, 2000), part bark of trunk 13% (Paula Susila, Stora Enso) and the assumption that only foliage and fine roots fall as litter before harvest. At harvest, everything but the stems are left at the ground.
LitterInput *(AWENH vectors for distribution of mass in R-script)*	Branches, bark, coarse roots: (0.65, 0.015, 0.015, 0.32, 0) Stumps: (0.75, 0.015, 0.015, 0.22, 0) Foliage: (0.31, 0.165, 0.165, 0.36, 0) Fine roots: (0.51, 0.05, 0.05, 0.39, 0)	Distribution between the AWENH fractions for each litter size as a vector.	Branches, bark, coarse roots (Ravina da Silva, 2014; Lemma *et al.*, 2007) Stumps (Ravina da Silva, 2014) Foliage (Lemma *et al.*, 2007) Fine roots (Lemma *et al.*, 2007) All values for the W and E compartments are calculated from the value for extractives split in two, since extractives includes both W and E.
WoodySize	Foliage: 0 Stumps: 17.5 Fine roots: 0.2 Branches, bark, coarse roots, tops: 5.1	cm	Foliage: Non-woody material is set to 0 (Yasso code). Stumps: Average stem diameter (Magdalena Pelufo, Stora Enso) Fine roots (Lemma *et al.*, 2007) Branches, bark, coarse roots, tops: mean of tops = 6 cm and branches 4.2 cm (Brick Chen, Stora Enso).

Table A6 Variables used and obtained in steady state simulations (for initial soil carbon content in eucalyptus forest modelling)

Variable	Input/output value	Units	Comment
InitialCPool	45	Mg C ha^{-1}	Porsö *et al.* (2016)
Initial AWEN	(0.5, 0.2, 0.1, 0.2)	Distribution between the AWENH fractions.	NB: No humus fraction here, this is adjusted manually for each location, see below.
Litter AWENH	(0.5, 0.2, 0.1, 0.2, 0.0)	Distribution between the AWENH fractions.	Average for grassland (Toni Viskari, FMI)
Litter mass	4	Mg C ha^{-1}	Porsö *et al.* (2016)

Woody size	0	cm	All litter is considered non-woody (Toni Viskari, FMI)
Veracel (Brazil)			
Initial humus fraction	0.76	Fraction of total soil carbon.	Adjusted during simulation and chosen to achieve steady state.
Result AWENH (year 1000)	(0.047, 0.005, 0.010, 0.252, 0.685)	Distribution between the AWENH fractions.	Distribution of total soil carbon between the AWENH fractions for year 1000.
Result soil C (year 1000)	51.32	Mg C ha^{-1} yr^{-1}	
Montes del Plata (Uruguay)			
Initial humus fraction	0.8	Fraction of total soil carbon.	Adjusted during simulation and chosen to achieve steady state.
Result AWENH (year 1000)	(0.066, 0.007, 0.009, 0.216, 0.701)	Distribution between the AWENH fractions.	Distribution of total soil carbon between the AWENH fractions for year 1000.
Result soil C (year 1000)	54.39	Mg C $ha^{-1}yr^{-1}$	
Guangxi (China)			
Initial humus fraction	0.78	Fraction of total soil carbon.	Adjusted during simulation and chosen to achieve steady state.
Result AWENH (year 1000)	(0.044, 0.004, 0.010, 0.232, 0.710)	Distribution between the AWENH fractions.	Distribution of total soil carbon between the AWENH fractions for year 1000.
Result soil C (year 1000)	50.12	Mg C $ha^{-1}yr^{-1}$	

Table A7. Biomass stock (Mg dry matter ha^{-1}) in eucalyptus plantations in Veracel, Brazil

Age (yr)	Leaves	Branches	Trunk	Stump	Coarse roots	Fine roots
1	4.2	4.3	8.2	1.9	1.2	2.2
2	3.1	3.8	31.5	4.4	2.8	2.7
3	2.0	3.3	54.8	6.9	4.4	3.3
4	2.5	4.2	66.0	7.6	4.9	3.3
5	2.9	5.1	77.1	8.2	5.5	3.3
6	3.4	6.1	88.3	8.9	6.1	3.3

Table A8. Biomass stock (Mg dry matter ha^{-1}) in eucalyptus plantations in Montes del Plats, Uruguay

Age (yr)	Leaves	Branches	Trunk	Stump	Coarse roots	Fine roots
1	4.2	4.3	8.2	1.9	1.2	2.2
2	3.5	3.9	23.7	3.6	2.3	2.5
3	2.7	3.6	39.3	5.2	3.3	2.9
4	2.0	3.3	54.8	6.9	4.4	3.3
5	2.5	4.2	66.0	7.6	4.9	3.3
6	2.9	5.1	77.1	8.2	5.5	3.3
7	3.1	5.5	80.8	8.5	5.7	3.3
8	3.3	5.8	84.5	8.7	5.9	3.3
9	3.4	6.1	88.3	8.9	6.1	3.3

Table A9. Biomass stock (Mg dry matter ha^{-1}) in eucalyptus plantations in Guangxi, China

Age (yr)	Leaves	Branches	Trunk	Stump	Coarse roots	Fine roots
1	4.2	4.3	8.2	1.9	1.2	2.2
2	3.5	3.9	23.7	3.6	2.3	2.5
3	2.7	3.6	39.3	5.2	3.3	2.9
4	2.0	3.3	54.8	6.9	4.4	3.3
5	2.5	4.2	66.0	7.6	4.9	3.3
6	2.9	5.1	77.1	8.2	5.5	3.3
7	3.4	6.1	88.3	8.9	6.1	3.3

Appendix 3 – External wood

The biogenic carbon fluxes for purchased wood was estimated based on wood delivered from external sources to Stora Enso's own mills (27.8 million m^3 sub) (Figure A2) and biogenic carbon fluxes for Stora Enso's own or leased forest land calculated in this report and other references for Central Europe (Table A10).

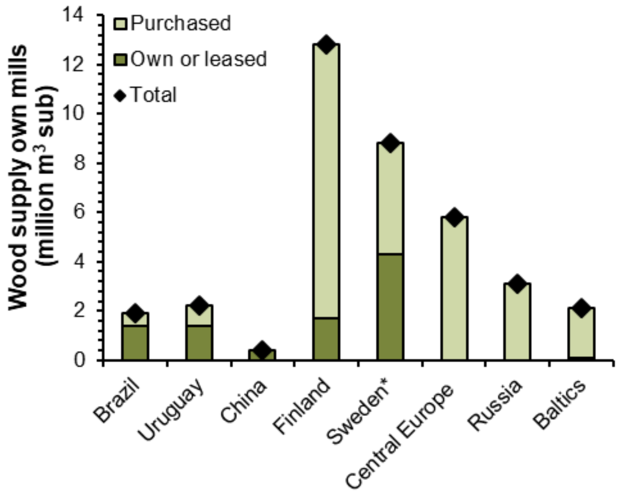

Figure A2. Wood delivered to Stora Enso's mills, from own or leased forest and purchased from external sources.

Table A10. Annual biogenic carbon fluxes and harvest used in carbon calculation of external wood, based on average for forest owned or leased by Stora Enso (sub = solid under bark)

Region	Carbon flux (Mg CO_2 ha^{-1})	Harvest (m^3 sub ha^{-1})
Brazil	-0,3	20,6
Uruguay	-0,1	13,7
China	-0,1	17,7
Finland	-0,6	4,4
Sweden	-1,1	3,6
Central Europe[a]	-0.8	5.8
Russia[b]	-0.9	4.0
Baltics[b]	-0.9	4.0

[a]Based on Austria's National Inventory Report (Environment Agency Austria, 2020) and statistics for roundwood removal (Eurostat, 2020b), [b]based on average for forest land in Sweden and Finland owned by Stora Enso.