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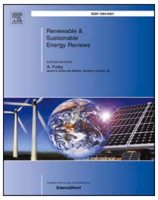

Does expanding wood use in construction and textile markets contribute to climate change mitigation?

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ABSTRACT

Wood use is expanding to new markets, driven by the need to substitute fossil-intensive products and energy. Wood products can contribute to climate change mitigation, if they have a lower fossil footprint than alternative products serving the same function. However, the climate change mitigation potential is contingent on the net fossil and biogenic emissions over time, as well as the realism of the counterfactual scenario and market assumptions. This study aims to improve the consistency of assessing the avoided fossil emissions attributed to changes in wood use, and to estimate the additional mitigation potential of increased wood use in construction and textile markets based on wood harvested in Finland. The results show that, compared to baseline, an increase in the market share of wood leads to an increase in atmospheric CO_2 concentration by 2050. Thus, the substitution impacts of wood use are not large enough to compensate for the reduction in forest carbon sinks in the short and medium term. This outcome is further aggravated, considering the decarbonization of the energy sector driven by the Paris Agreement, which lowers the fossil emissions of competing sectors more than those of the forest sector. The expected decarbonization is a highly desirable trend, but it will further lengthen the carbon parity period associated with an increase in wood harvest. This creates a strong motive to pursue shifts in wood uses instead of merely expanding all wood uses.

1. Introduction

The emphasis in bioeconomy innovation clusters' research and innovation programs has shifted from high volume bioenergy uses towards high value-added material uses such as bioplastics, pharmaceuticals, food and feed additives, bio-composites, and construction materials [1]. The same applies to the forest sector, whose product portfolio is expected to diversify from graphics papers to a wide range of new uses, notably in construction and textiles [2,3]. The positive market prospects are partly driven by expectations on the climate change mitigation potential of wood products [4]. This study focuses on residential wood-frame multi-story construction and regenerated cellulosic fibers (RCFs), as these two markets have been identified to hold clear potential for market expansion and several innovations have already been commercialized [5].

Wood products can mitigate climate change both through carbon storage and through substitution. The biogenic carbon that is transferred from forest to products may cause either net emissions or removals depending on the annual balance of the amount of wood entering the market and the amount of wood flowing out of the market and eventually back to the atmosphere [6]. Although wood products may displace more fossil emission-intensive products or energy carriers, and thus avoid greater fossil emissions [7,8], wood harvest also affects biogenic carbon net removals in forest ecosystems over time. This reduces the climate benefit of increasing industrial wood use in the short to medium term [9].

The climate change mitigation potential of wood use can be defined as the marginal change in net greenhouse gas (GHG) emissions compared to a baseline scenario [10,11]. A large body of literature assesses the net GHG emissions of the forest sector against a baseline scenario. Most studies indicate that in the case of increased level of harvest, the positive climate change mitigation effects of increased carbon storage in wood products, and in material and energy substitution, are smaller than the reduction in forests carbon sinks in a timeframe of up to a century. Such conclusions have been derived for the EU [12], Japan [13], Sweden [11,14], Canada [15], France [16], Switzerland [17], Austria [18], and Finland [10,19]. In the boreal

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Nomenclature

Abbreviations

DF	displacement factor
DOM	dead organic matter
GHG	greenhouse gas
LCA	life cycle assessment
RCF	regenerated cellulosic fiber

Notation

BPE	byproduct equivalent
cc	carbon content of oven dry product
D	demand for roundwood
d	dry-fresh density
DFW	Weighted displacement factor
DOM	carbon stock in dead organic matter
EU	share of an end use among all end uses of an intermediate wood product
FU	share of a functional unit among all functional units in an end use of a wood product
l	volumetric loss
NCE	net carbon equivalent emission
OF	annual outflow of a wood product from the wood product pool
PC	carbon stock in harvested wood product pool
RWE	roundwood equivalent
S	supply of intermediate wood product
SI_P	overall substitution impact for the production stage
SI_EOL	overall substitution impact for the end-of-life stage
TC	carbon stock in standing tree biomass
wc	air dry water content
WU	amount of biogenic carbon contained in wood used in a product
y	product output per material input (yield)

Indexes

e	end use
f	functional unit
i	wood product or energy carrier
j	non-wood product or energy carrier
k	scenario
0	baseline scenario
t	year

Units

CO_2eq	carbon dioxide equivalent
C	fossil or biogenic carbon
GWP_{100}	global warming potential with annualized CO_2 equivalents over 100 years($CO_2eq./yr$)
J	joule
m^3	cubic meter
t	tonne
Wh	watt hour

conditions, including surface albedo and the formation of biogenic secondary organic aerosols enforces the trade-off between short-term and long-term benefits of wood use [20]. However, the mitigation potential is affected by the scale of substitution impacts, which varies greatly depending on assumptions [21,22].

Studies focusing on the net climate impacts of the Finnish forest sector emphasize forest management measures and find that net emissions can be reduced by increasing growing stock biomass [23], prolonging rotations to produce more sawlogs [23], postponing the thinning of young stands [24], using pulpwood, logging residues, coarse roots and stumps as biofuel [24–26], fertilization [27], favoring long-lived products [23], and recovering discarded products for energy use [23]. Globally, most studies quantifying material substitution impacts focus on wood construction and indicate that the fossil-based emissions of wood-based houses are 20–50% lower than those of thermally comparable houses built primarily of steel or concrete [28]. However, this result does not consider biogenic carbon emissions and removals, which typically lead to opposite conclusions in a timeframe of decades up to a century. Mishra et al. [29] indicate that a strong increase in wood construction globally could lead to large net GHG emission reductions even when considering the biogenic emissions and removals, but this result is attributed to afforestation in response to the increased roundwood demand, and remains therefore subject to interpretation.

A few studies examine the effect of changes in product portfolios. Chen et al. [30] find that allocating all increased harvest to structural panels would result in immediate net emission reductions, as compared to a delay of 84 years with current wood uses. Brunet-Navarro et al. [31] assume that the end uses of wood can be shifted without increased harvest, e.g., by moving the use of low-quality logs from paper production to engineered wood products, resulting in immediate net removals. Similarly, Hurmekoski et al. [32] suggest that there may be more potential in the reallocation of byproducts from energy to material uses such as textiles and composites rather than changing forest management to increase the share of wood construction.

Literature on the climate change mitigation potential of the forest sector places more emphasis on the estimation of the biogenic carbon cycle and forest management activities than on the detailed assumptions required for estimating avoided fossil emissions. Yet, recent literature contests even some of the fundamental premises underlying substitution impact estimates: The reduction of average GHG emissions in all sectors driven by efforts to comply with the Paris Agreement reduces the ability to avoid further fossil emissions through wood use [31]. Also, the direct substitutability of wood-based designs against alternative designs is based on uncontested assumptions [33]. A few studies consider international carbon leakages [34], but intersectoral or intertemporal leakages have been ignored. For example, if the use of wood avoids greater fossil fuel use in the construction sector, part of the fossil fuel use that was avoided in the construction sector may be used by a third party or later in time [35].

There is an urgent need for updating and improving the consistency of substitution impact estimates related to changes in wood use to inform the analysis of the climate change mitigation potential of the forest-based sector. Against this backdrop, the aims of the study are threefold: i) to improve the consistency of assessing the avoided fossil emissions attributed to wood use, ii) to provide a state-of-the-art substitution impact estimate for wood harvested in Finland, and iii) to examine the additional mitigation potential of increased use of wood in two emerging markets –multi-story residential construction and textile fibers.

2. Methods and data

2.1. Calculation framework and system boundary

The study explored the additional climate change mitigation potential of wood products produced from wood harvested in Finland, including logs, pulpwood, and energy wood, and excluding imported woody biomass. The additional mitigation potential was evaluated as the difference in net carbon equivalent emissions in market scenarios compared to a baseline scenario. The net carbon emission (see section

2.6) is a mid-point estimate based on the GWP_{100} method, i.e., global warming potential with annualized CO_2 equivalents over 100 years (CO_2eq./yr), and encompasses biogenic carbon stock change in trees, soil (dead organic matter, DOM) and product pool, as well as caused and avoided fossil emissions attributed to wood use (substitution impacts).

There is no single established practice for quantifying the net emissions and removals resulting from changes in wood use. The approaches are based on industrial ecology and employ, e.g., life cycle assessment (LCA), material flow analysis, and forest simulation modelling. Fig. 1 presents the overall calculation framework used in this study. The baseline scenario followed a top-down approach starting from the supply of intermediate products taken from various statistical sources, followed by the disaggregation of the end uses of intermediate products and the definition of substitution cases, i.e., which wood product can be expected to substitute for which non-wood product. The substitution cases were related to displacement factors (DFs) based on secondary LCA data. This allowed calculating weighted DFs for each intermediate product.

Using spreadsheet substitution models as an extension of forest sector models or forest management models represents the common practice in literature, but it suffers from the uncontrollable number of end uses, functional units, and substitution cases leading to major data gaps. To address this issue, an inverse approach was used in the market scenarios, in which the starting point of the analysis was the functional unit instead of harvested wood assortment [cf. 36]. Functional unit quantifies the qualitative and quantitative aspects of the functions that a product provides [37], such as a square meter in a specific building type, ensuring comparability among the products that serve the same function. The inverse approach allowed producing more detailed estimates for the market scenarios, which, together with the marginal change approach, reduces the significance of the uncertainties caused by data gaps in the baseline.

2.2. Material flows

Fig. 2 shows the allocation and relative volumes of wood flows from roundwood assortments into intermediate products and byproducts. The supply of intermediate products was determined exogenously as per the scenario assumptions (see section 2.7). The supply and use of byproducts and the roundwood demand were calculated from the supply of intermediate products (see also Supplementary information 1). Due to the scarcity of official statistics, the byproducts were treated as an aggregate pool with no distinction among the types of byproducts, except for solid vs. liquid byproducts whose technical utilization potential differs remarkably. The byproduct generation in primary industries and allocation to secondary material and energy applications, and the roundwood yields in the baseline were calibrated to match the official statistics of intermediate product and energy supply and roundwood harvest to the extent possible, given minor data gaps and inconsistencies between data sources. This was done by finetuning the most uncertain roundwood yields for sawnwood, plywood, and chemical pulp, so that the model reproduced the official product and energy supply and log and pulpwood harvest statistics for 2020 (±0.01 Mm^3) [38,39]. Additionally, the 2020 wood use statistics were corrected for net trade to capture only the wood harvested in Finland.

2.3. Biogenic emissions and removals in forests

The carbon stocks and carbon balances of forests comprised living wood biomass and dead organic matter (DOM). The dynamics of these carbon stores were simulated separately for each forest inventory plot. The biomass stock of living wood biomass was initialized with the inventory data (tree species, breast height diameter, and height of the trees measured in the plot) and the biomass models of Repola [40,41]. The biomass models separately predicted the dry mass of the stem, stump, branches, foliage, and coarse roots. The biomass of fine root was predicted based on the biomass of foliage. The carbon content of different biomass components was predicted from dry mass, using species-specific conversion factors (about 50% of dry biomass is carbon).

The growth, survival and ingrowth of trees were simulated using the individual-tree models of Pukkala et al. [42]. The biomass and carbon stock of living trees were calculated based on simulations of the stand development with a 5-year time step. The 5-year carbon balance of living woody biomass was obtained as the difference in the carbon stock between the end and the beginning of the 5-year time step.

The biomass stock of DOM was initialized using the Pukkala models [43] and the DOM decomposition was simulated with the Yasso15 model [44,45]. Inputs to the DOM pool consisted of annual litter fall, dead trees, and harvest residues. The litter yield was calculated using turnover rates, specified separately for tree species, and biomass

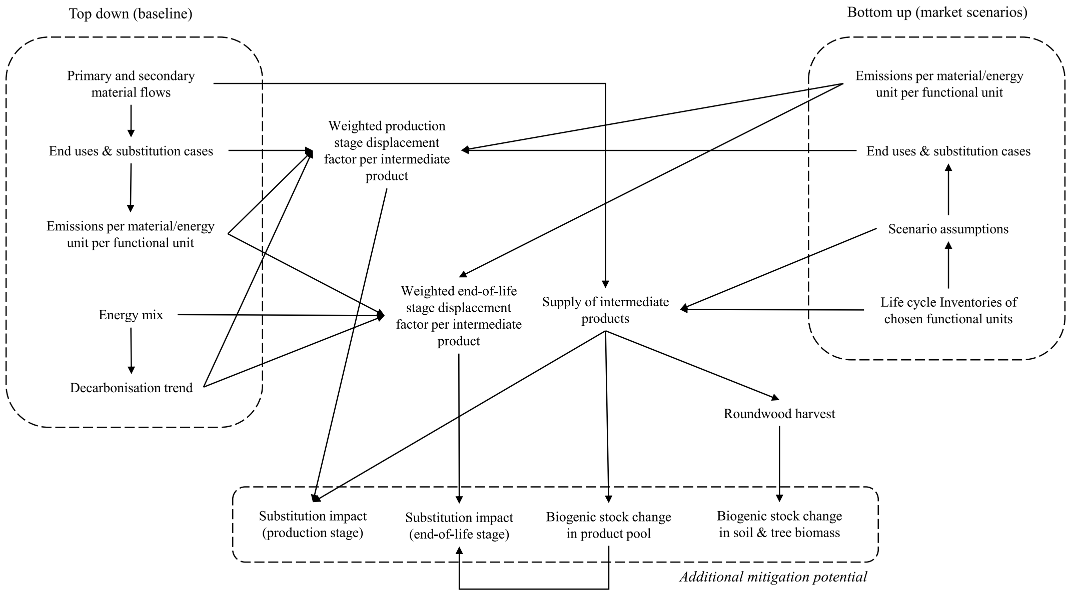

Fig. 1. Calculation framework and data flow.

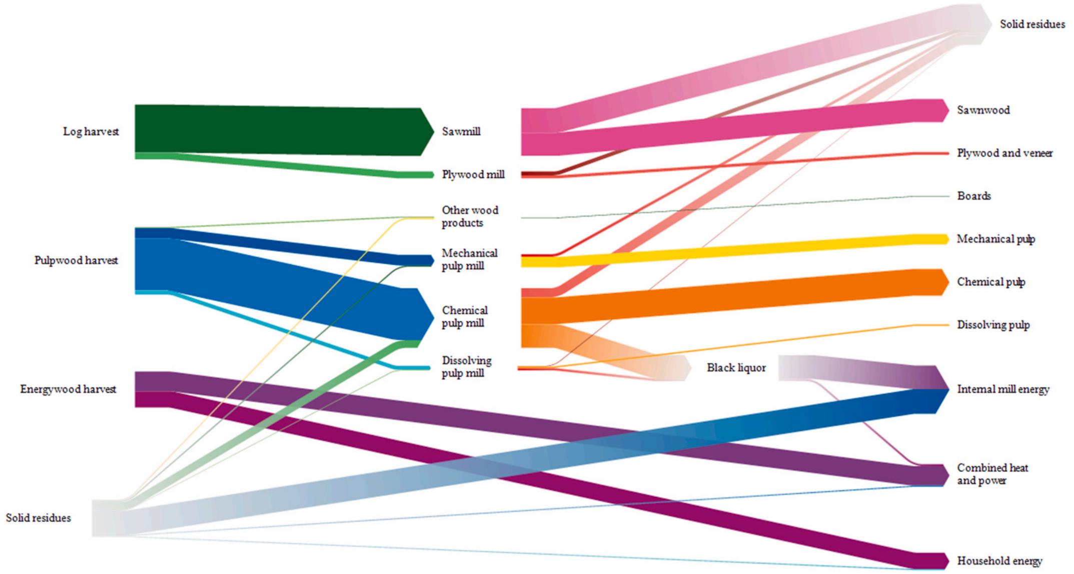

Fig. 2. Wood flows from harvest to intermediate products for the baseline scenario. The width of the flows indicates the relative volumes in dry tons of biogenic carbon.

components (branches, foliage, coarse roots, and fine roots). The turnover rate gives the proportion of living biomass that is shed as litter during a year. The entire biomass of trees that were predicted to die during a 5-year time step was transferred to the DOM pool. Harvest residues were another type of DOM input, and consisted of the branches, treetops, foliage, stumps, coarse roots, and fine roots of the harvested trees. However, it was assumed that two-thirds of the biomass of branches and treetops was collected in clear-felling and transported away from the forest.

In peatlands, the growth and decomposition of peat were additional components of the carbon dynamics of DOM. In non-drained peatland, the peat was assumed to grow corresponding to an annual carbon removal of 0.25 tC/ha [46,47]. No peat growth was assumed in drained peatlands. Instead, the aerobic peat layer was assumed to decompose according to the Yasso15 model. The thickness of the decomposing peat layer was calculated from ditch depth, growing stock volume, latitude, and summer precipitation [48]. The dynamics of DOM of tree origin were simulated in the same way as in upland mineral soils.

The 5-year carbon balance of DOM was calculated as the difference between 5-year DOM input (litter, dead trees, harvest residues, peat growth) and decomposition of the DOM stock over 5 years. More detailed descriptions of the calculation of biogenic carbon emissions and removals in forests have been discussed in Ref. [47].

The initial state of the simulation data was derived from a subsample of the sample plots of the 11th National Forest Inventory (NFI11, 2009–2013) of Finland [49]. Simulations were performed separately for southern, central, and northern Finland, as in Heinonen et al. [19]. Several alternative treatment schedules were simulated for each plot. Optimization was used to select such a combination of the treatment schedules, which maximized the objective function. The objective was to maximize the profitability of forest management (net present value with a 3% discount rate) while meeting the harvesting targets specified for four 10-year periods. In all three harvesting scenarios, the annual roundwood harvest targets presented in Table 1 were based on the market scenarios presented in section 2.7. More detailed description of the optimization method is available in Heinonen et al. [19,50]. Supplementary information 1 gives additional information on the simulation of alternative treatment schedules for the plots.

2.4. Biogenic emissions and removals in wood product pool

The biogenic emissions and removals from the wood product pool

Table 1
Annual roundwood harvest targets for the simulation.

		2016–2025		2026–2035		2036–2045		2046–2055	
		Log	Pulp	Log	Pulp	Log	Pulp	Log	Pulp
Baseline	SF	12.41	14.47	12.41	14.96	12.41	15.45	12.41	15.94
	CF	8.15	12.60	8.15	13.03	8.15	13.46	8.15	13.89
	NF	4.23	11.52	4.23	11.91	4.23	12.31	4.23	12.70
	Total	24.79	38.59	24.79	39.90	24.79	41.22	24.79	42.53
Construction	SF	12.41	14.47	12.49	14.96	12.56	15.45	12.63	15.94
	CF	8.15	12.60	8.20	13.03	8.25	13.46	8.30	13.89
	NF	4.23	11.52	4.25	11.91	4.28	12.31	4.30	12.70
	Total	24.79	38.59	24.94	39.90	25.09	41.22	25.23	42.53
Textiles	SF	12.41	14.47	12.41	15.56	12.41	16.67	12.41	17.76
	CF	8.15	12.60	8.15	13.56	8.15	14.52	8.15	15.48
	NF	4.23	11.52	4.23	12.39	4.23	13.27	4.23	14.15
	Total	24.79	38.59	24.79	41.51	24.79	44.46	24.79	47.39

SF = Southern Finland, CF = Central Finland, NF = Northern Finland.

(often referred to as harvested wood products, HWP) were calculated with the 'production approach', as defined by the IPCC [6], in which carbon inflows to, and outflows from, the product carbon pool were tracked based on the supply of intermediate wood products originating from a single country and the default average half-lives of intermediate wood products. The stock change was initiated with the period from 1961 to 2050 to allow the stocks to saturate before the beginning of the scenario period. The data for 1961–2020 were taken from statistics [38], the values for 2050 were derived from the market scenarios and the values for 2021–2049 were imputed with linear regression.

2.5. Substitution impacts

On the level of a single functional unit, the substitution impact was quantified using a displacement factor (DF), which expresses how many units of fossil carbon are avoided per unit of biogenic carbon contained in a wood product (see Supplementary information 1). The DF is given as:

$$DF_f = \frac{GHG_i - GHG_j}{WU_i - WU_j} \qquad \text{(Eq. 1)}$$

where DF_f = functional unit specific displacement factor, GHG_i and GHG_j = fossil GHG emissions resulting from the use of functionally equivalent wood (i) and non-wood (j) substitutes expressed in CO_2 equivalents over a timeframe of 100 years, and WU_i and WU_j = the amounts of biogenic carbon contained in wood used in the wood product (i) and non-wood product (j) [51]. A negative value implies avoided fossil emissions.

The DFs for material uses were calculated from comparative LCA studies providing the GWPs for representative, functionally equivalent wood products and non-wood products (see supplementary information 2). The DFs for novel RCFs were derived from openly available summaries of preliminary LCA assessments for the Spinnova® and Kuura® fibers. The energy used within wood product mills in the production of wood products was not credited to avoid double counting the substitution benefits of material and energy uses of wood, as the material substitution benefits arise to a significant extent from the use of wood byproducts to cover the energy demand of the mills [36].

Energy DFs were calculated separately for a functional unit of MWh of power or heat, based on lower heating values of various materials and fuels, conversion efficiencies, unit emissions, and market share trajectories of energy production technologies (see Supplementary information 1). Of the total amount of energy produced from woody biomass, 17.3% was assumed to be power produced in combined heat and power (CHP) facilities, and the rest was heat either in stand-alone district heating plants or in CHP facilities. No stand-alone power was assumed to be produced from wood biomass. All direct energy use of wood (forest energy and energy produced from byproducts sold outside mills) was assumed to be consumed in Finland and to replace the Finnish average energy mix. The end-of-life credits arising from the energy recovery of material products were calculated based on the global average energy mix, as most wood products produced in Finland are exported globally.

Supply-volume-weighted displacement factor (DFW) for intermediate product i was defined as:

$$DFW_i = \sum_{e=1}^{E}\left(EU_{ei}\sum_{f=1}^{F}FU_{fei}DF_f\right) \qquad \text{(Eq. 2)}$$

where EU_{ei} is the share of end use e among all end uses of intermediate wood product i (%), E is the number of end uses, FU_{fei} is the share of functional unit f among all functional units in end use e of wood product i (%), F is the number of functional units, and DF_f is the functional unit specific DF (tC/tC).

Wood products may also substitute for each other. No separate DFs were calculated for substitution between wood products, as the denominator of DF_f would be zero. Instead, substitution between wood products is reflected as different weights for the DFW.

Importantly, the substitution impacts of wood use can be expected to fall in the future, due to climate change mitigation efforts across all sectors, as there will be fewer fossil emissions to be avoided [e.g., 31]. To account for this effect, the rate of fossil emission reduction in the energy sector was calculated from 2020 to 2050 based on the EU reference scenarios [52] and the world energy outlook [53], and the DFs estimated for 2020 were multiplied by the rate of energy emission reduction each year. Note that with this approach, the emissions of both wood products and non-wood products are reduced, but the relative reduction is larger for non-wood products, as they are currently higher, on average.

The overall substitution impact for the production stage (SI_P) was given by:

$$SI\_P_t = \sum DFW_{it} \times S_{it} \qquad \text{(Eq. 3)}$$

where DFW_i = the volume weighted DF for wood product i (tC/tC), S_i = the supply of intermediate wood product i (MtC/yr), and t = year. A negative value stands for avoided fossil emissions compared to no wood use, while a positive value stands for higher emissions compared to no wood use.

The overall substitution impact for the end-of-life stage (SI_EOL) was given by:

$$SI\_EOL_t = \sum DF\_EOL_{it} \times OF_{it} \qquad \text{Eq. (4)}$$

where DF_EOL_i = the end-of-life DF for wood product i (tC/tC), OF_i = the annual outflow of wood product i from the wood product pool (MtC/yr), and t = year.

As overall substitution impacts (avoided emissions compared to no wood use) are not directly comparable to absolute emissions and removals reported in national GHG inventories (stock change compared to previous period), the overall substitution impact was calculated merely as an intermediate step to allow calculation of marginal (additional) substitution impacts [see also 36].

2.6. Net carbon emissions

The net carbon emissions were given as:

$NCE_t = -(TC_t - TC_{t-1}) - (DOM_t - DOM_{t-1}) - (PC_t - PC_{t-1}) - SI\_P_t - SI\_EOL_t$ (Eq. (5)).

Where TC = tree carbon stock, DOM = dead organic matter carbon stock, PC = product carbon stock, SI_P_t = avoided fossil emissions attributed to wood use at the production stage of the product lifecycle, SI_EOL_t = avoided fossil emissions attributed to wood use at the end-of-life stage (energy recovery) of the product lifecycle, and t = year. A negative value stands for net removals.

The climate change mitigation potential of a scenario was defined as the difference in the net emissions between the market scenario and the baseline scenario:

$$\Delta NCE_{kt} = NCE_{kt} - NCE_{0t} \qquad \text{(Eq. 5)}$$

Table 2
Scenario assumptions.

Scenario	i. Baseline	ii. 30% market share increase in multi-story residential construction	iii. 30% market share increase in textiles
Sawnwood, wood-based panel, and plywood supply	- no change	- 50% of the mid-rise buildings are cross-laminated timber frame and 50% light frame; life cycle inventory data based on the average of two separate analyses based on similar building designs [60,61] - stagnating overall housing demand	–
Chemical pulp supply	- increase of 9.3% from 2020 to 2050 [54]	–	- increases driven by a 15% increase in market share of novel RCFs
Dissolving pulp supply	- increases driven by quadrupling of RCF demand (based on the projected mid-term growth rate for 2021–2030 [55], and textile market grows from 109 to 250 Mt/yr [62]): RCF market share increases from 5.3% to 9%	–	- increases driven by a 15% increase in market share of contemporary RCFs
Changes in end uses	- given that the compound annual growth rate for viscose is around 50% lower than that of lyocell, assumed 4% compound annual growth rate for viscose and 8% for non-viscose RCFs; share of viscose of all RCFs declines from 90% to 74.8% - supply of communication papers reduced by 50%, which shifts to packaging in the end uses of mechanical and chemical pulp - energy sold outside mills remains at 2020 level, despite increased energy efficiency, as the fossil emissions of the wood product mills are reduced through increased byproduct use to cover mill's own energy consumption.	–	- the demand for viscose equals that of the baseline, while the rest of the demand shock is satisfied by non-viscose RCFs; the share of viscose of all RCFs declines from 74.8% to 33.3% - energy sold outside mills reduces to zero, due to increased energy consumption of pulp mills with integrated textile fiber manufacture

where NCE_k is the net carbon emission in scenario k, NCE_0 is the net carbon emission in the baseline scenario, and t is year. A negative value stands for marginal net removals compared to baseline.

2.7. *Market scenarios*

Three scenarios from 2020 to 2050 were formulated, including a baseline and two "what if" scenarios that foresee a 30% increase in demand for specific wood-based functional units in construction and textile markets, *ceteris paribus*. The scale of change represents a major deviation from business-*as*-usual but was not considered unreachable. Table 2 summarizes the scenario assumptions. The scenarios imply changes both in the volume of intermediate products produced and in the end-use distribution of intermediate products, thus affecting not only the production volumes but also the weighted DFs.

In the baseline scenario, the demand growth assumptions for intermediate products were taken from Kallio et al. [54], foreseeing an overall increase of 9.3% for chemical pulp production and no change for the solid wood product industries by 2050. In terms of end uses, the only assumed change was a 50% reduction in the supply of graphic paper (newsprint and printing and writing), driven by substitution for electronic media, and a corresponding percent increase in packaging, driven by increased e-commerce. To avoid overestimating the additional mitigation potential of the market scenarios, more detailed assumptions were also considered for multi-story construction and textiles for the baseline: rapid growth for wood-based textiles was already assumed for the baseline, based on most recent mid-range projections [55], with the market share of RCFs increasing from 5.3% to 9% and the share of viscose of all RCFs declining from 90% to 74.8% (see Table 2). However, for multi-story construction, no deviation from baseline was assumed for the market share of wood or for the construction activity, as no clear long-term trends could be identified in the market share and construction activity was expected to stagnate in the EU due to stagnating population growth.

In the construction scenario, the market share of wood-frame multi-story construction in the EU was assumed to increase by 30% from near zero [56]. The functional unit was one square meter in a typical residential multi-story building in the Nordic countries, which was generalized to cover the whole EU market. A 50% share of the increase was assumed for light timber frames and 50% for cross-laminated timber (CLT) frames, which corresponds to the market situation in Finland in

Table 3
Assumptions on price-mediated market effects for the scenarios: assumed impact of a one unit increase in the global demand of intermediate wood products on the roundwood harvest in Finland and on the end-use distribution of intermediate wood products produced in Finland.

	Wood-frame multi-story construction	Regenerated cellulosic fibers
Log harvest	In proportion to Finland's global market share of sawnwood in 2020: 3.1% increase.	No impact, due to increased share of thinnings and shorter rotation period.
Pulpwood harvest	No impact, due to residues displacing pulpwood from thinnings and lengthened rotation period.	In proportion to Finland's global market share of chemical pulp in 2020: 4.75% increase.
Proportion of shift in end uses	No shift in end uses.	20% increase in roundwood harvest; 80% shift from chemical pulp to dissolving pulp and from other end uses of chemical pulp to textiles.
Overall impact on roundwood harvest	3.1% increase in log harvest.	0.95% increase in pulpwood harvest.

2020 [57].

In the textile scenario, the market share of RCFs globally was assumed to increase from around 6%–36%. The functional unit was one tonne of staple fiber. A 50% share of the increase in demand was assumed for established RCFs and 50% for novel fibers represented by Spinnova® and Kuura®, which conforms to stated mid-range investment plans. Within the established RCF market, the supply of viscose was assumed to remain at the same level as in the baseline, while the remainder of the increased demand was assumed to be covered by non-viscose RCFs (modal and Lyocell).

Table 3 outlines assumptions considering price-mediated market effects, based on a review of results of forest sector model projections for similar scenarios in previous literature [3,12,58,59]. Firstly, given the system boundary of the analysis was restricted to wood harvested in Finland, scenarios ii and iii assumed that the level of harvest in Finland responds to an increase in the EU demand for construction and global demand for textiles only in proportion to Finland's global market share of sawnwood and chemical pulp, respectively. Secondly, an increased harvest of logs was not assumed to result in increased harvest of pulpwood, nor vice versa. That is, even though pulpwood and log supply is to an extent integrated, the ratio of log to pulpwood harvest varies, due to, e.g., rotation periods, thinning intensity, minimum top diameter, and other quality criteria set for sawlogs, as well as substitution between byproducts and pulpwood. Thirdly, the increase in demand may only partially lead to investments in new production capacity. That is, an increase in demand for a certain functional unit may lead to a shift in wood use from one end use to another, with no impact on the supply of intermediate products. However, due to the scarcity of literature addressing shifts in end uses, this was only considered in the context of textiles, for which Kallio [59] suggests that only around 20% of the additional demand for textile fibers is satisfied by new pulp capacity. Considering the price-mediated effects, a one unit increase in global demand was assumed to lead to a 3.10% and 0.95% increase in the supply of intermediate wood products produced in Finland in the construction and textile scenarios, respectively.

3. Results

Fig. 3 shows that both the construction scenario and the textile scenario indicated increased net emissions to the atmosphere by 2050,

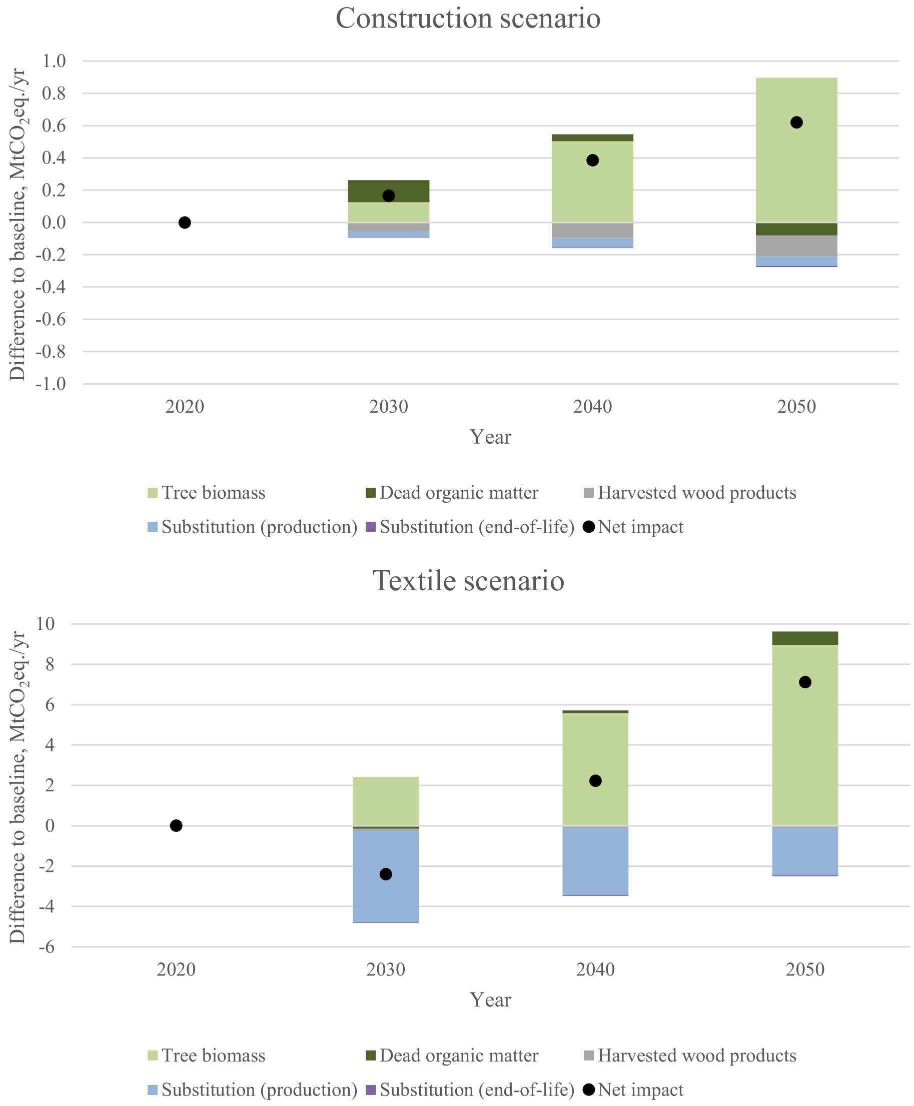

Fig. 3. Difference in net emissions and their constituents compared to baseline. Negative values stand for increased removals and positive values stand for increased emissions, compared to the baseline scenario.

Table 4
Impact of market scenarios on roundwood harvest and net emissions in 2050.

	2020	Baseline	Construction	Textiles
Roundwood harvest (excl. energywood), Mm^3	58.38	62.32	62.76	67.18
Difference to baseline, Mm^3			0.44	4.86
Difference to baseline, %			0.7%	7.8%
Log harvest	24.79	24.79	25.23	24.79
Difference from baseline, Mm^3			0.44	0.00
Difference from baseline, %			1.8%	0.0%
Pulpwood harvest	33.59	37.53	37.53	42.39
Difference from baseline, Mm^3			0.00	4.86
Difference from baseline, %			0.0%	12.9%
	2020	Baseline	Construction	Textiles
Substitution impact (production stage), MtCO$_2$eq./yr	−12.55	−4.59	−4.65	−6.93
Difference from baseline, MtCO$_2$eq./yr			−0.06	−2.35
Difference from baseline, %			−1.3%	−51.2%
Substitution impact (EoL), MtCO$_2$eq./yr	−5.25	−2.05	−2.06	−2.11
Difference from baseline, MtCO$_2$eq./yr			−0.01	−0.05
Difference from baseline, %			−0.3%	−2.5%
Wood product pool emissions and removals, MtCO$_2$eq./yr	−3.10	−1.90	−2.03	−2.01
Difference from baseline, MtCO$_2$eq./yr			−0.13	−0.11
Difference from baseline, %			−6.9%	−6.0%
Tree biomass emissions and removals, MtCO$_2$eq./yr	−15.27	−34.81	−33.91	−25.86
Difference from baseline, MtCO$_2$eq./yr			0.90	8.95
Difference from baseline, %			2.6%	25.7%
Soil biomass emissions and removals, MtCO$_2$eq./yr	20.67	−3.30	−3.38	−2.62
Difference from baseline, MtCO$_2$eq./yr			−0.08	0.68
Difference from baseline, %			−2.5%	20.5%
Net impact, MtCO$_2$eq./yr	na	na	na	na
Difference from baseline, MtCO$_2$eq./yr			0.62	7.11
Difference from baseline, %			1.3%	15.3%

compared to baseline. That is, the carbon removals by the wood product pool and the avoided fossil emissions were not large enough to compensate for the decline in forest carbon removals, compared to the baseline scenario. Table 4 shows that the increase in emissions was minor for the construction scenario, around 0.6 MtCO$_2$eq./yr, because the additional wood harvest was minor, which limited the impact on biogenic carbon removals. Moreover, the DFs and average lifespan of products for wood-frame multi-story construction were comparable to those for the existing functional units related to wood construction, which resulted in very minor changes for the substitution impacts and wood product emissions and removals.

For the textile scenario, the increase in carbon emissions was remarkably higher, around 7.1 MtCO$_2$eq./yr. The increase in substitution impacts was at first, in 2030, able to offset the reduced forest carbon removals due to an increase in the average DF attributed to the shifts in wood uses away from graphic and hygienic papers and packaging to textiles. However, this outcome was reversed after 2030, driven by the decarbonization of the energy sector.

Table A1 summarizes the weighted DFs per intermediate product and lifecycle stage. The weighted DF for the entire wood use was 0.23 tC/tC for the production stage and 0.25 tC/tC for the EoL stage in 2020. In the baseline scenario, these values were reduced to 0.08 and 0.09 tC/tC by 2050, primarily due to the expected decarbonization of the energy sector. The construction scenario had no effect on the weighed DF in 2050. The textile scenario improved the production stage DF from 0.08 to 0.11 tC/tC but had no effect on the weighted EoL DF.

4. Discussion

4.1. *Biogenic versus fossil emissions and removals*

In this study, the weighted DF for the entire wood use declined from 0.23 to 0.08 tons of fossil carbon avoided per tons of biogenic carbon contained in wood products (tC/tC) for the production stage only and from 0.33 tC/tC in 2020 to 0.12 tC/tC including EoL benefits to 2050 in the baseline scenario.[1] This was notably smaller compared to estimates in previous studies, in which the weighted DF ranges from 0.34 to 0.66 tC/tC for the production stage only [21,32,63], and from 0.56 to 1.2 tC/tC including EoL benefits [10,23,32] in baseline scenarios. Main reasons for the difference include the projected decarbonization of the energy sector, assuming wood energy to replace an average energy mix instead of a marginal fossil fuel (see section 4.2), and making a more detailed allocation of intermediate products to end uses and functional units. An additional reason can be that previous studies may have calculated the fossil emissions of wood value chains separately, whereas this study calculated net substitution impacts capturing both caused and avoided fossil emissions in wood value chains to avoid double counting and non-counting.

In comparison, an additional ton of biogenic carbon harvested from the forest reduced the carbon sink by 2.4–2.7 tons of carbon (tC/tC), corresponding to 1.8 to 2 tCO$_2$eq./m^3. This can be interpreted as the threshold displacement effect that the avoided fossil emissions and wood product removals ought to reach to provide short-term and medium-term climate benefits. It compares to an estimated average of 1.6 tC/tC in a previous literature review [64]. Both the low substitution impact and the high biogenic carbon opportunity cost explain the clear net emission increase associated with increased wood use in this study. This reinforces the findings of previous literature (see section 1), with few exceptions [65].

The results indicate that the increased harvest of domestic wood, regardless of the wood products portfolio, would represent a challenge for the Finnish forest-based bioeconomy from the viewpoint of climate change mitigation: Increased harvest in Finland cannot be justified by short- or medium-term climate change mitigation. If the GHG emissions of the land-use sector cannot be decreased in Finland, the pressure to increase the carbon sink of forests will increase. This can be done, at least to an extent, by measures other than decreased harvests, e.g., by increased forest fertilization and the use of improved forest regeneration material [e.g., 50]. However, the potential negative impacts of intensified wood production on water systems, genetic diversity and forest resilience ought to be considered. Also the GHG emissions from peatlands should be reduced, e.g., by avoiding ditch network maintenance and using continuous cover forestry, as in the simulations of this study [66,67].

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[1] Note that Table A1 presents the production stage and EoL stage DFs separately. These may be incomparable as the production stage DF is calculated per unit C contained in wood products produced in year t, while the EoL DF is calculated per unit C contained in the outflow from wood product pool in year t. However, for comparison purposes, the average DF presented here is determined as the sum of production stage and EoL stage substitution impact divided by the carbon contained in annual harvest.

4.2. Substitution assumptions

Substitution cannot be measured or verified, as it only occurs relative to a hypothetical counterfactual development, i.e., a trajectory that never came to existence due to the activity under study. Therefore, assumptions play a decisive role in the estimation of substitution impacts. Early literature on the climate change mitigation potential of the forest sector often referred to substitution impacts, but either did not attempt to quantify them, or only included bioenergy [68]. Later studies quantified the substitution impacts relying on life cycle assessment approaches particularly in the construction sector [11]. Recent literature has raised the need for more dynamic assumptions on the evolution of the substitute technologies and on market responses [33]. Applying more detailed assumptions may lead to dramatically lower substitution impact estimates compared to previous literature [35], which conforms to the outcome of this study. A yet more comprehensive examination of substitution dynamics may eventually lead to reversed conclusions: In case of imperfect substitution, the overall fossil emissions may increase instead of decrease with expanding wood use [69]. Arriving at more detailed estimates requires revising core assumptions related to the existence and rate of substitution, the rate of decarbonization and its impacts on avoided fossil emissions, and indirect market responses caused by changes in wood uses.

The major weakness of current substitution analyses is that there are no systematic means of identifying the substitute products [e.g., 33]. In LCA, the definition of substitutes is strongly related to the definition of a functional unit. However, while this concept allows the impacts of wood and non-wood products to be compared, it does not imply or measure the existence or rate of substitution on market level. Thus, the selection of the substitute remains subject to judgment.

One particular assumption concerns whether a wood product substitutes for a single alternative product or an average market mix, and this discussion has centered particularly around energy. For example, studies may assume wood to substitute for coal in heat production, or an average energy mix in power production [e.g., 36]. The choice of the reference fuel significantly influences the scale of the substitution impact estimates, as the unit emissions of the average energy mix are considerably lower than those of a marginal fossil fuel.

According to Ekvall & Weidema [70], average data are typically used for attributional LCA, while marginal data are typically used for consequential LCA. However, the marginal technology may not be the same within the time frame of 1 h, one year or one decade [71]. The short-term marginal technology is typically the cheapest form of providing one additional unit of an output on an hour-by-hour basis. In the long term, as argued by Mathiesen et al. [72], a change cannot be considered marginal if it affects the trend of the market. One must also account for technological development and structural changes. Thus, it is not possible to accurately determine one marginal technology for long-term decision support [72].

To emphasize long-run decision support, in this study, wood was assumed to displace an average heat or electricity mix, instead of a single marginal technology. In Finland, coal power will be phased out by law from 2029 onwards, and the replacement will be a mix of different technologies, including natural gas, woody biomass, and renewable energy sources. One can argue that, by 2050, wood cannot be assumed to substitute for fossil fuels any more in Finland. In this case, one can either assume that there are no other large-scale replacements for wood in heat production, or the replacements such as nuclear power or geothermal heat have very minor fossil emissions. Either way, the displacement factor can be assumed to be zero or close to zero.

One can further argue that the choice of the substitute technology requires taking an even longer time horizon. One cannot assume that wood would replace fossil fuels indefinitely, as the avoided fossil resource use cannot exceed the actual fossil resource stock, as noted by Harmon [35]. This relates to the assumed reference fuel: the key question is, which other energy source would have been used, if not wood? Before the fossil era, there were no other options than wood and other biomass, so there were no substitution impacts. The same analogy holds for the future, in that fossil feedstocks are finite and should be phased out long before the exhaustion of the economically viable reserves. However, for the time being, there is no systematic framework to judge the exact point in time at which one can no longer assume wood to substitute for fossil feedstocks: in the absence of a consistent framework, it is argued that the assumption of replacing the average energy mix in future projections serves as a useful proxy for the evolution of the substitute technologies, or the lack thereof.

Besides being able to name the substitute products, one ought to be able to assess the rate of substitution [see 73]. Again, there is no systematic framework to assess this. If it was considered, however, the average substitution impact would be further reduced, as only part of an additional unit of wood products produced would substitute for alternative products, while part of it would merely add to the overall supply to the market [73]. Lastly, one ought to consider indirect price-mediated market impacts, such as rebound effects and leakages. One can conclude that despite arriving at significantly lower substitution impact estimates compared to previous literature, more detailed future research may reduce them further.

4.3. Market assumptions

One of the major assumptions affecting the results is the extent to which a one unit increase in global demand increases the wood harvest in Finland. This can be split into two separate assumptions. Firstly, it was assumed that the competitiveness of the Finnish forest sector remains unchanged, i.e., the current global market share of Finland in the supply of intermediate products remains unchanged. Changes in the market share would require national subsidies to cover increased costs or major investments in more efficient production capacity to lower fixed costs.

Secondly, a one unit increase in demand may result in less than one unit increase in overall harvest, as part of the increased supply may result from a shift away from other end uses of intermediate products. This study considered such shifts based on forest sector model projections for similar scenarios found in previous literature looking into the market response of increased supply of wood for construction [12,58] and textiles [3,59]. However, evidence of shifts in end uses was only available for the textile market [59], and not for the construction market. As the increase in harvest in the construction scenario was minor, a stronger relative impact on harvest can be justified. This contrasts with Brunet-Navarro et al. [31], who assumed the increase in demand for wood construction products to be satisfied by a shift in wood uses from papers to solid wood products, which helps to explain the opposite conclusion on the climate change mitigation potential in this study. It should also be noted that no changes in the utilization of sidestreams were assumed in this study: If they were partly redirected from primary energy use to low emission and long lifetime material uses, the average benefit of wood use could improve, provided that the internal energy use of mills could be satisfied with alternative low emission sources.

The overall impact of the construction scenario remained minor. Expanding the construction scenario to cover single family buildings would have doubled the estimated roundwood removal and therefore the net emission impact, but the overall marginal change in wood use and in net emissions would still have remained smaller compared to textiles. This raises the question as to which end uses the use of wood could expand as much as to multiply the sawnwood consumption per capita in Europe [e.g., 58], given that a 100% market share in the residential construction market in the EU implies only doubling the current consumption per capita. Thus, it remains unknown which non-wood products could be substituted and in which functional units. However, this study is in line with the findings of Eriksson et al. [58] in that even a moderate increase in the market share of wood construction in Europe may have minor consequences on wood use and on net emissions.

4.4. Limitations

It is worth emphasizing that the results of this study remain contingent on the counterfactual scenario, i.e., what would have happened in the absence of increased wood use, and the definition of the system boundary, i.e., the extent that affecting factors have been considered and accurately quantified. The study relies on a host of assumptions that are based on previous literature and the judgment of the authors. Future research should conduct systematic uncertainty and sensitivity analysis of the assumptions and work towards covering the remaining analytical gaps and perfecting the approaches presented. For example, a systematic approach is required for reliably identifying substitute products and services, as well as the rate of substitution, e.g., through econometrics. Also, new models are needed for assessing the feasibility of shifts in the end uses of intermediate products, as it critically affects the demand for primary wood and therefore the biogenic carbon cycle. Future analyses may also benefit from using alternative climate metrics to track the impacts across different timeframes [74]. Importantly, while a fully comprehensive consequential LCA exercise may be unfeasible with the system boundary of this study, it would be important to increase efforts towards this direction. In particular, general equilibrium modelling could be used to capture price-mediated changes in the other processes and systems of the economy, such as investments and divestments in production capacity and rebound effects [37].

It should be noted that wood use has also other effects than carbon emissions and removals. For example, favoring RCFs in place of cotton reduces the need for fresh water for irrigation, obviates the need for pesticides, and releases land for afforestation or food production [75]. However, more intensive forest management may conflict, e.g., with biodiversity targets [76]. Covering a more comprehensive set of sustainability indicators would allow more comprehensive assessment and decision support.

5. Conclusions

The study contributes to literature on the climate change mitigation potential of the forest sector by providing a consistent framework for assessing the change in net GHG emissions caused by changes in wood use, by identifying critical assumptions affecting the substitution impact estimates, and by producing a comprehensive estimate of the substitution impacts of wood harvested in Finland through case studies on construction and textile markets. In particular, the study improves existing substitution impact estimates by providing more detail for all wood uses, considering the effect of decarbonization targets on the potential to avoid further fossil emissions, and by providing explicit justifications for market and substitution related assumptions.

The results show that an increase of 30% in the market share of wood in residential multi-story construction markets and textile fiber markets lead to a net increase in the atmospheric GHG concentration by 2050, when both biogenic carbon and fossil carbon are considered. The tradeoff between the short-term and long-term climate impacts of wood harvest is driven both by a high opportunity cost for forest carbon sinks associated with an increase in the harvest level and the expected decarbonization of the energy sector to comply with the Paris Agreement. Neglecting the long-term emission evolution of competing industries leads to inflated substitution impact estimates. The expected decarbonization is naturally a highly desirable trend, but it will lengthen the carbon parity period associated with an increase in wood harvest [77], which in turn will place more emphasis on the biogenic carbon cycle. This creates a strong motive to pursue shifts in wood uses, as opposed to merely expanding all existing wood uses. New research methods are required to inform on the feasibility of such shifts. Finally, as the diminishing substitution impacts demotivate climate change mitigation strategies based on substitution alone, the emphasis in climate change mitigation efforts could be shifted towards low carbon pathways considering all materials and services within a sector and examining the limits of primary material consumption.

Credit author statement

Elias Hurmekoski: Conceptualization, Data curation, Funding acquisition, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Janni Kunttu: Data curation, Validation, Writing – original draft. Tero Heinonen: Formal analysis, Writing – original draft. Timo Pukkala: Software, Writing – original draft. Heli Peltola: Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113152.

Appendix 1

Table A1
Weighted displacement factors for wood products based on wood harvested in Finland.

Current (2020)	DF (prod.), tC/tC	Prod. volume, MtC	DF (EoL), tC/tC	Outflow, MtC	Subst. impact (prod.), MtCO$_2$eq./yr	Subst. impact (EoL), MtCO$_2$eq./yr	Subst. impact (total), MtCO$_2$eq./yr
Coniferous sawnwood	0.96	2.26	0.24	1.40	7.95	1.22	9.17
Non-coniferous sawnwood	0.84	0.01	0.16	0.02	0.03	0.01	0.04
Plywood & veneer	0.51	0.29	0.27	0.22	0.55	0.21	0.76
Particle board	0.36	0.03	0.41	0.09	0.04	0.13	0.17
Hardboard	0.32	0.02	0.38	0.01	0.03	0.02	0.05
Chemical pulp	0.10	2.61	0.26	2.67	0.92	2.50	3.42
Mechanical pulp	0.06	1.02	0.26	1.14	0.23	1.07	1.31
Dissolving wood pulp	−0.63	0.14	0.19	0.12	−0.33	0.08	−0.25
Pulping waste	0.02	4.52			0.27		0.27
Energywood	0.57	1.19			2.46		2.46
Solid residues	0.04	2.58			0.41		0.41
Total	0.23	14.67	0.25	5.67	12.55	5.25	17.80
Baseline scenario (2050)	DF (prod.), tC/tC	Prod. volume, MtC	DF (EoL), tC/tC	Outflow, MtC	Subst. impact (prod.), MtCO$_2$eq./yr	Subst. impact (EoL), MtCO$_2$eq./yr	Subst. impact (total), MtCO$_2$eq./yr
Coniferous sawnwood (incl. EWPs)	0.35	2.26	0.09	1.79	2.91	0.57	3.48
Non-coniferous sawnwood	0.31	0.01	0.06	0.01	0.01	0.00	0.01
Plywood & veneer	0.19	0.29	0.10	0.26	0.20	0.09	0.29
Particle board	0.13	0.03	0.15	0.05	0.01	0.03	0.04
Hardboard	0.12	0.02	0.14	0.02	0.01	0.01	0.02
Chemical pulp	0.07	2.59	0.09	2.59	0.69	0.89	1.58
Mechanical pulp	0.10	1.02	0.09	1.02	0.37	0.35	0.72
Dissolving wood pulp	−0.13	0.47	0.07	0.45	−0.23	0.11	−0.11
Pulping waste	0.00	5.02			0.06		0.06
Energywood	0.11	1.19			0.47		0.47
Solid residues	0.01	2.69			0.08		0.08
Total	0.08	15.59	0.09	6.19	4.59	2.05	6.64
Construction scenario (2050)	DF (prod.), tC/tC	Prod. volume, MtC	DF (EoL), tC/tC	Outflow, MtC	Subst. impact (prod.), MtCO$_2$eq./yr	Subst. impact (EoL), MtCO$_2$eq./yr	Subst. impact (total), MtCO$_2$eq./yr
Coniferous sawnwood (incl. EWPs)	0.35	2.30	0.09	1.80	2.96	0.57	3.54
Non-coniferous sawnwood	0.31	0.01	0.06	0.01	0.01	0.00	0.01
Plywood & veneer	0.19	0.29	0.10	0.26	0.20	0.09	0.29
Particle board	0.14	0.03	0.15	0.06	0.02	0.03	0.05
Hardboard	0.12	0.02	0.14	0.02	0.01	0.01	0.02
Chemical pulp	0.07	2.59	0.09	2.59	0.69	0.89	1.58
Mechanical pulp	0.10	1.02	0.09	1.02	0.37	0.35	0.72
Dissolving wood pulp	−0.13	0.47	0.07	0.45	−0.23	0.11	−0.11
Pulping waste	0.00	5.02			0.06		0.06
Energywood	0.11	1.19			0.47		0.47
Solid residues	0.01	2.71			0.08		0.08
Total	0.08	15.66	0.09	6.21	4.65	2.06	6.71
Textiles scenario (2050)	DF (prod.), tC/tC	Prod. volume, MtC	DF (EoL), tC/tC	Outflow, MtC	Subst. impact (prod.), MtCO$_2$eq./yr	Subst. impact (EoL), MtCO$_2$eq./yr	Subst. impact (total), MtCO$_2$eq./yr
Coniferous sawnwood	0.35	2.26	0.09	1.79	2.91	0.57	3.48
Non-coniferous sawnwood	0.31	0.01	0.06	0.01	0.01	0.00	0.01
Plywood & veneer	0.19	0.29	0.10	0.26	0.20	0.09	0.29
Particle board	0.13	0.03	0.15	0.05	0.01	0.03	0.04
Hardboard	0.12	0.02	0.14	0.02	0.01	0.01	0.02
Chemical pulp	0.26	2.29	0.09	2.31	2.19	0.79	2.98
Mechanical pulp	0.10	1.02	0.09	1.02	0.37	0.35	0.72
Dissolving wood pulp	0.18	1.09	0.07	1.03	0.72	0.26	0.98
Pulping waste	0.00	5.55			0.00		0.00
Energywood	0.11	1.19			0.47		0.47
Solid residues	0.00	2.80			0.04		0.04
Total	0.11	16.55	0.09	6.49	6.93	2.11	9.04

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