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Carbon Credits Through Wood Use: Revisiting the Maximum Potential and Sensitivity to Key Assumptions

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ABSTRACT

Wood use generates technosphere carbon credits (TCCs) through avoided fossil-based emissions and net sequestration of carbon into the technosphere (harvested wood products and geological storage). We investigated how large and uncertain TCCs of wood use per carbon harvested are considering the current and alternative ways of using wood, and the effects of the decarbonization of societies over 25-, 50-, and 100-year time horizons. We applied stochastic simulation and scenario analysis using Finnish market structure as a baseline to demonstrate the use of the TCC calculator created. The mean value of TCCs of wood use were between 0.2 and 0.5 t_C/t_C with an uncertainty range from 0.1 to 0.8 t_C/t_C, depending on the scenario. The uncertainties were mainly concerned with the extent to which (1) fossil-based emissions are avoided through substitution (displacement factors) and (2) fossil-based raw materials are substituted (substitution rates). Assumptions on the decarbonization of societies reduced TCCs of wood use significantly over time. TCCs of wood use can be increased by directing wood into uses that substitute fossil-intensive materials and have a long lifetime, such as construction materials, and increasing energy recovery and avoiding emitting carbon at the end of life of harvested wood products by carbon capture and storage. However, they were very likely to be considerably lower than forest carbon debits resulting from harvesting additional wood for substitution under all considered circumstances and under a wide but reasonable range of stochastic parameter values. Thus, the result emphasizes the need to reduce overall consumption of goods to mitigate climate change.

1 | Introduction

Wood harvesting operations influence atmospheric carbon dioxide (CO_2) balances by altering forest carbon stocks, harvested wood product (HWP) carbon stocks, and fossil-based emissions (Soimakallio et al. 2021; Soimakallio et al. 2016). These effects should be accounted for in a system analysis when the studied wood use is compared to a reference system without the studied wood use (Cowie et al. 2021; Koponen et al. 2018). Such an approach allows assessment of how additional wood use affects the atmospheric CO_2 balances.

Harvesting more wood results in reduced forest carbon stock compared to harvesting less in a reference system (i.e., *forest carbon debit*) (Soimakallio et al. 2022), but it can help to avoid fossil-based CO_2 emissions when the increased wood is used as a substitute for nonrenewable materials or energy. This *substitution effect* takes place primarily when the wood replaces fossil-based materials or energy and at the end of life of HWPs by energy recovery. In addition, the carbon stock in HWPs can be increased by producing more long-living HWPs than in the reference system, thus extending the storage time before carbon release by energy recovery or natural decomposition. According to the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas reporting practices, increase in the biogenic carbon stock is accounted for as carbon removal from an atmospheric perspective (Pingoud, Kenneth, and Daniel 2006). Here, we call the joint effect of avoiding fossil emissions, and increased carbon storage (removal) in the HWP pool and geological storage as *technosphere carbon credits* (TCCs) from wood use.

Based on average estimates in recent literature reviews, forest carbon debits are often significant compared to TCCs for current wood use at the market level (Hurmekoski et al. 2021; Soimakallio et al. 2022). In addition, decarbonization of energy and material production and consumption processes in societies will further reduce the potential of wood use to avoid fossil carbon emissions by substituting alternative materials and energy for wood because the overall fossil emissions are reduced. These aspects create fundamental challenges for using wood to mitigate climate change in the short and medium term (Leturcq 2020; Soimakallio et al. 2021).

A host of data and assumptions are needed for the quantification of TCCs, some of which are inherently uncertain, rendering the precise quantification of TCCs impossible, if adopting a broad system boundary. Besides the variation in the production stage and end-of-life stage emissions associated with a product, a core uncertainty is the estimation of fossil emissions avoided when opting for wood-based products over more fossil-intensive alternatives due to the reliance on hypothetical assumptions and scarcity of data (Harmon 2019; Myllyviita et al. 2021). Even some of the fundamental premises underlying the estimation of the substitution effect have been recently questioned (Howard et al. 2021). Notably, current literature implicitly assumes that wood-based products are perfect substitutes for nonwood alternatives, that is, that a 1-unit increase in the supply of wood-based products reduces the supply of alternative products or energy by 1 unit (Harmon 2019), normalized to the functional unit or reference flow in question. However, there is very little evidence about the extent to which substitution occurs at the market level (Hurmekoski et al. 2022).

This study conducts a systematic uncertainty assessment of the factors affecting TCCs from wood use. While it is unrealistic to capture all assumptions in detail given the wide system boundary, a consistent calculator with reasonable parameter value ranges, including the rate of decarbonization and the rate of substitution, greatly helps to pin down the overall uncertainty range of TCCs. The study demonstrates the use of the TCC calculator created using Finnish market structure as a baseline for the wood product supply. Due to international trade of wood products, the TCCs are calculated with EU or global averages, where applicable.

The fundamental aim of this study is to quantify the uncertainties of TCCs and to identify opportunities to increase them. First, we estimated TCCs for intermediate product level and with the production structure of Finnish forest industry over 25, 50, and 100 years under various decarbonization scenarios and assuming various end-of-life energy recovery options. The production structure of Finnish forest industry was chosen as Finland is one of the largest wood-producing countries in the world and required data are available. Next, we identified the most influential parameters affecting the uncertainty of TCCs. Finally, we compared TCCs to forest carbon debits, discussed the potential to increase TCCs, and drew conclusions. More specifically, we sought to answer the following questions:

1. What is the magnitude of TCCs for various intermediate wood products and energy options separately and for total wood use with the production structure of Finnish forest industry?
2. What is the effect of uncertainties related to substitution effects and HWP net removals and the different rates of decarbonization of societies on the overall TCCs?
3. What are the effects of alternative end-of-life energy recovery options on the overall TCCs?
4. What is the contribution of uncertainties in various input parameters on the total uncertainty of TCCs?

2 | Methods

We started by constructing an assessment tool to estimate TCCs (see SI1). The tool, created with Microsoft Excel (version 2308), can be used to calculate TCCs over time (in our setting up to 100 years) for a desired forest harvest scenario. Here, it was assumed that annual wood demand of a studied wood use structure increased by 1 unit compared to a hypothetical reference system in which the demand did not increase. Note that for calculating the overall climate effects, the changes in forest carbon stocks resulting from forest management (i.e., forest carbon debits) to provide the increased demand for wood should be estimated and accounted for separately.

2.1 | Harvest Data, HWPs, and Wood Energy Categories

We included four forest harvest assortments that can typically be obtained from any forest simulator: logs, pulpwood, energy wood, and residues. The proportions of harvest assortments influence the amounts of HWPs and wood energy, and hence the overall TCCs.

Wood flow from each harvested wood assortment is distributed into six intermediate products, specifically sawn wood products, plywood and veneer, particle- and fiberboards, chemical-, dissolving-, mechanical-, and semichemical pulp, and to five energy uses, specifically combined heat and power (CHP), household heat, biofuel and heat, biochar and heat, and bioenergy with carbon capture and storage (BECCS). The selection of these categories was based on data availability and properties to cover the key product groups. We used the Finnish distribution of assortments as outlined in Section 2.8.

2.2 | Substitution Effect

Changes in fossil emissions due to wood use are expressed through substitution effects. Weighted displacement factors (DFs) were defined for each intermediate product by weighting the functional unit-specific DFs per the share they represent of the total consumption of each intermediate product. Functional unit refers to the scale at which life cycle assessment is conducted, comparing pairs of wood-based and nonwood-based products expressing the same function, such as m^2 of heated floor area of a specific building type. However, due to the vast number of possible end uses for all wood-based products, most of the substitution cases were determined at the level of intermediate wood-based products (normalized to reference flows), such as 1 ton of textile fibers, which could be used for a number of end-use functions. Furthermore, partly because of comparing mostly intermediate products instead of end-use functions, we considered the possibility of imperfect substitution between wood and nonwood products, distinguishing between the proportion of wood product supply that is a substitute for alternative products and energy, and the proportion that merely expands the total supply in a market (Hurmekoski 2024). Thus, the weighted net DF (WNDF) for an intermediate wood-based product I was calculated as:

$$\mathrm{WNDF}_I = \sum_{i=1}^{I} {}^{c_i}/_{c_I} \left(\sum_{j=1}^{J} \mathrm{sr}_{ij} \left(\frac{\mathrm{GHG}_i - GHG_j}{\mathrm{WU}_i - WU_j} \right) \right) + \sum_{i=1}^{I} {}^{c_i}/_{c_I} \left(\sum_{j=1}^{J} \left(1 - \mathrm{sr}_{ij}\right) \left(\frac{\mathrm{GHG}_i}{\mathrm{WU}_i} \right) \right) \quad (1)$$

where C_i/C_I is the proportion of function i of all end uses of intermediate wood-based product I, sr_{ij} is the *substitution ratio* defined as the percentage change in the consumption of nonwood function j caused by a 1% change in the consumption of wood-based function i, GHG_i and GHG_j = fossil-based GHG emissions ($tCO_2eq./t$) over a timeframe of 100 years resulting from the production of functionally equivalent wood (i) and nonwood (j) substitutes, and WU_i and WU_j = the amounts of biogenic carbon contained in wood used in the wood function (i) and nonwood function (j). In the extreme case of no substitution ($sr = 0$), the former part returns zero and only caused emissions remain. At the other extreme of perfect substitution ($sr = 1$), the latter part of the equation returns zero and only avoided emissions remain.

The system boundary for the GHG emissions was cradle to gate (from resource extraction to factory gate, excluding use, and end of life) for the material uses of wood and cradle to grave (from resource extraction to end of life) for the energy uses of wood. The end-of-life GHG emissions were determined separately, as the production stage effects (primary production) arise from different wood flows than the end-of-life effects (outflow from HWP pool), so using a single aggregate DF for the entire life cycle multiplied by the annual production of wood products would be inconsistent. The use phase of the compared products was excluded, as it was considered mostly independent of the materials used and would not have been possible to reliably assess in the chosen framework.

The unit emission and wood use values were adapted from Hurmekoski et al. (2023) (see Table S4). The DFs for heat or electricity sold to grid in biochar production and BECCS were assumed to be the same as for CHP. For biofuel, we used values based on Koponen et al. (2013) and Hurmekoski et al. (2023).

2.3 | End-of-Life Substitution

The weighted DF for the end-of-life stage was defined with the same equation as for the production stage (Equation 1). The end-of-life substitution effect was calculated by multiplying the end-of-life DF with the annual outflow of biogenic carbon from the product pool (see Section 2.6 below). The end-of-life substitution benefit mostly arises from the energy recovery of discarded wood products, which can replace more fossil-intensive energy carriers. The options for the six intermediate products considered were 'no energy recovery' at end-of-life and four end-of-life energy recovery options, including heat/heat and power, biofuel and heat, biochar and heat, and BECCS.

2.4 | Temporal Development of Societal Decarbonization

We contrasted three scenarios of societal decarbonization based on IEA (2021). Specifically, we obtained DFs based on these scenarios.

- Static ignores decarbonization and assumes that the DFs remain unchanged in the future.
- Business as usual (BAU) extrapolates the current decarbonization roughly following the IEA's "Stated policies scenario" and "Announced pledges scenario" assuming the unit emissions of energy are halved in the Year 2050 and are a quarter of the emissions of the Year 2021 in 2120.
- NetZero2050 follows IEA's "Net zero emissions by 2050" ambitious path assuming 11% emissions per energy unit in the year 2050 compared to current emissions. We assumed no emissions by the year 2120.

Years in between were interpolated linearly in both BAU and NetZero2050.

2.5 | Internal Process Energy

We included internal process energy parameters for each of the intermediate and energy products considered. These parameters reflect the proportion of the input wood that is consumed in the products' manufacturing stage. The need for internal process energy demand can be met either from wood or other energy sources. When using more wood to meet the energy demand for manufacturing primary products, fewer sidestreams are available for secondary products. When using less wood, more external energy is needed, resulting in lower DFs, unless the external energy source is fossil emission free. Selecting the proportion of biomass used for internal mill energy gives the option to direct sidestreams into the production of energy or intermediate products simultaneously decreasing the DF of the primary product, or decreasing the external energy needed in manufacturing the primary product while increasing its DF.

2.6 | Biogenic Carbon Sequestration Into Technosphere

The net effect of biogenic carbon inflow to and outflow from the HWP pool, that is, net removals, was calculated with the 'production approach' according to the IPCC (Rüter et al. 2019). Carbon inflows to and outflows from the HWP carbon pool were tracked annually based on the supply of intermediate wood products. Default average half-lives were used for intermediate wood products. The half-life of biochar in the soil depends on multiple factors, such as the pyrolysis temperature, the soil conditions, and qualities of the wood material. Here, we assumed a half-life of 345 years based on average values relevant to boreal conditions (Maestrini et al. 2014; Santos, Torn, and Bird 2012; Zimmerman 2010). Carbon captured in geological storage can be assumed to remain indefinitely, but here we erred on the side of caution and assumed a half-life of 500 years for BECCS which, however, makes little difference in timeframes up to a century.

The outflow of carbon depends on the lifetime of HWPs and the application of technologies providing carbon capture and storage functions. For CHP, household heat, and biofuel production, carbon is assumed to be released in the year of wood harvesting. The lifetime of carbon in HWPs, biochar, and geological storage is based on the first-order decay function and half-life assumptions according to the Tier 1 method of the IPCC GHG inventory guidance (Rüter et al. 2019). The stock change model was not initiated with historical data since here the purpose was to examine the effect of supplying an additional unit of a certain forest product or forest product portfolio compared to a reference system.

2.7 | TCCs

The total TCC attributed to wood use was calculated based on an established framework (e.g., Gustavsson et al. 2017), modified by considering imperfect substitution (see Hurmekoski 2024). Thus, TCC was determined as:

$$\mathrm{TCC}_t = \sum \frac{\left(\mathrm{PC}_{It} - \mathrm{PC}_{It-1}\right) + C_{It} \times \mathrm{WNDF}_{It} + \mathrm{OF}_{\mathrm{It}} \times \mathrm{WNDF\_EOL}_{It}}{C_t} \tag{2}$$

where PC is the product carbon stock, C_I is the supply of intermediate wood product I (t C/yr), $WNDF_I$ is the weighted net DF for intermediate wood product I (see equation 1), OF_I is the annual outflow of intermediate wood product I from the wood product pool (tC/yr), $WNDF\_EOL_I$ is the weighted net DF at end of life for intermediate wood product I (t_C/t_C), C is the amount of biogenic carbon in the total harvest, and t is time.

2.8 | Description of the Default Simulation

The initial production structure for the forest industry was based on Finnish conditions due to the availability of relatively accurate data. A default simulation was created assuming that the proportions of harvest assortments in Finland in 2022 would continue for 100 years and that the input wood would be used in the same way as it is used today. Realistic market shift scenarios were not considered here to better isolate the influence of methodological and parameter uncertainties so that the wood use structure was effectively considered as one source of uncertainty. Of the wood harvested in 2022, 40% was sawn wood logs, 45% pulpwood logs, and 15% small diameter wood (energy wood) (Luke 2022). The input wood was divided into intermediate uses and energy uses following the production structure of Finland (Luke 2023) using raw material efficiencies and internal energy requirements acquired from the various references and works cited (for more details see SI1). To take uncertainties into account, we varied the values of input parameters (see 2.9. *Uncertainty and sensitivity analysis* below) within each of the three decarbonization scenarios for the DFs selected based on IEA (2021) (see 2.4 *Temporal development of societal decarbonization*).

2.9 | Uncertainty and Sensitivity Analysis

Many of the simulation parameters were approximations based on simplified assumptions, such as the DFs and the rates of substitution. To investigate the effect of uncertainties on the TCCs, we conducted a sensitivity analysis of the TCCs to the key parameters. We generated a range for the key parameters and applied Monte Carlo simulations to estimate the TCC sensitivity. For each input parameter, a triangular probability distribution was assumed based on the most representative mode value and minimum and maximum values defined, see SI1.xls.

For the weighted DFs, the probability distribution was formed using minimum, maximum, and mode values (Hurmekoski et al. 2023; Valada et al. 2016). The minimum and maximum values of weighted DFs were determined by screening the range of available values for two parameters. Firstly, the unit emissions of wood products and substituted products varied depending on production routes, LCA calculation methods, and geographical scope (regions where the products produced in Finland are exported). Secondly, the exact proportions of each functional unit of the total consumption of the intermediate products were unknown. Thus, the range represented the variance based on estimates both for the unit emissions representing uncertainties in life cycle inventories and for the proportions of functional units representing estimates in different regions in Europe.

For WNDF, the rate of substitution (the proportion of wood products displacing functionally equivalent fossil products) was an unknown parameter for most wood uses, yet assuming perfect substitution appeared unrealistic, given an empirical substitution ratio of 30%–50% for wood-based textile fibers (Hurmekoski 2024). In the absence of further empirical evidence, conservative values of a minimum of 80%, an average of 90%, and a maximum of 100% were used for all wood uses other than textiles. The minimum was higher for other wood uses, as one can argue that wood-based building materials and energy carriers are closer substitutes to nonwood counterparts than textile fibers, whose properties differ more from their potential substitutes. That is, it is still reasonable to assume that if wood was not used in a building, a building would still have likely been built, except for very specific types of buildings such as summer cottages or huts (see SI1 for more detailed assumptions and references).

The proportion of energy recovery of all end-of-life options was based on a European average value of 20% (Cazzaniga, Jasinevičius, and Mubareka 2022), with 10% minimum and 90% maximum to cover the large uncertainty and lack of accurate data. For the half-lives of carbon affecting the HWP emissions and removals, the default uncertainty range provided by IPCC (Rüter et al. 2019) was used. The half-lives were 35 years, 25 years, and 2 years for sawnwood, plywood and boards, and pulp products, respectively, with an uncertainty range of 50%.

For the other input parameters (yield of wood products and wood energy, internal process energy demand, and HWP densities), we used average values from the literature and created four uncertainty classes (5%, 10%, 25%, and 50% uncertainty) following the principles of data quality pedigree matrix (Edelen and Ingwersen 2018). These classes were applied to form ranges for parameter values, for example, a parameter value of 1 in 25% uncertainty class would have a range of 0.75–1.25 used in the simulations. Thus, all probability distributions were symmetrical except for the DFs where we applied minimum and maximum values from the literature, and for the end-of-life energy recovery rate, where global average from literature was used for a starting point with a wide range of uncertainty. A global average was used, as most of the wood product supply in Finland/European Union is exported globally, yet it would be practically infeasible to trace the wood flows to all regions and end uses.

The uncertainty analysis was calculated by using an open-source Excel plugin "Simulacion 5.0". A total of 10,000 simulation replicates were used in each given analysis. The replicates were also used to test for the sensitivity to the input parameters using Spearman's rank correlations (ρ). If the value of ρ was higher than 0.1, the contribution of a parameter to the uncertainty of TCC was considered significant. See SI3 for simulated replicates.

3 | Results

3.1 | TCCs by Intermediate Product Type

The highest cumulative TCCs per harvested carbon over 100 years assuming the BAU decarbonization scenario and excluding utilization of sidestreams (any other than for internal energy need) and end-of-life energy recovery were achieved via mechanical wood products (sawn wood, plywood and veneer, and boards) ranging from 0.3 to 0.4 t_C/t_C (Figure 1). TCCs for pulp were considerably lower (−0.2 to 0.1 t_C/t_C), where a negative value implies increased net emissions. The negative value for dissolving pulp was due to the assumption that dissolving pulp produced in Finland is exported to Asia to produce viscose, and the viscose produced in Asia has a larger fossil carbon footprint than cotton (Shen, Worrell, and Patel 2010). Burning of the wood in CHP plants and in households or as in biofuel gave 0.2 t_C/t_C TCCs per unit of wood, while there was higher potential in energy uses retaining carbon, such as biochar and BECCS where TCCs ranged from 0.5 to 1.1 t_C/t_C. Moreover, biochar and BECCS provided even higher TCCs compared to producing HWPs from wood when assuming decarbonization of the society, as they contribute mainly to carbon sequestration (Tables S1 and S4). The total TCCs from sawn wood, plywood and veneer,

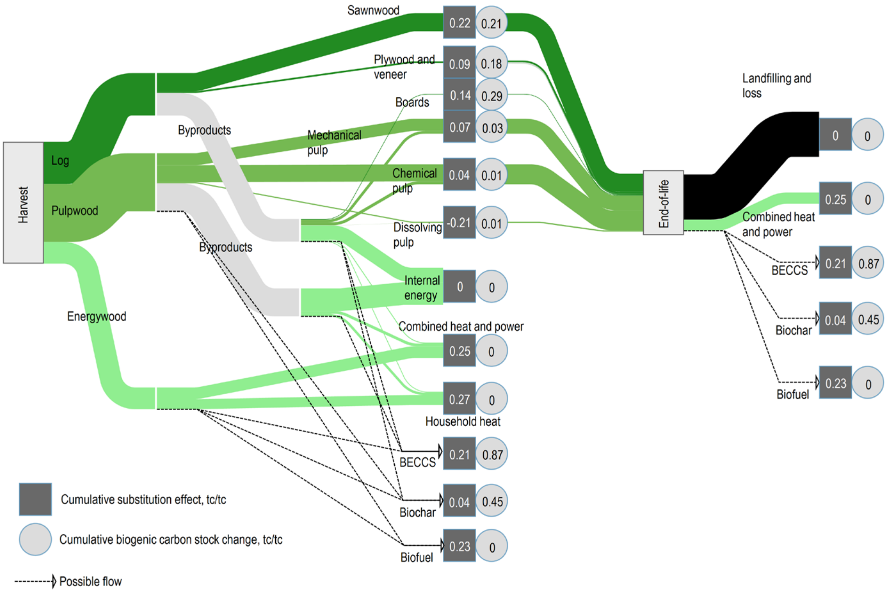

FIGURE 1 | Substitution effect and net carbon removal from the atmosphere allocated to intermediate products and energy products per carbon contained in wood harvest in cumulative terms over 100 years assuming BAU decarbonization scenario. The TCCs of each intermediate product or energy product are the sum of the cumulative substitution and biogenic carbon stock change. The flow chart represents the structure of wood use in the default simulation, while the black dotted arrows represent alternatives for wood energy uses. The estimates account for uncertainties in all input parameters based on averages from a simulation with 10,000 replicates. See BAU definition in Section 2.4.

and boards increased 9%–26% when considering the use of sidestreams and end-of-life energy recovery (See Tables S1a,b). For chemical-, dissolving-, and mechanical pulp, the TCCs increase was 22%–80%.

3.2 | Overall Uncertainty of the TCCs

Cumulative TCCs per carbon in harvested wood varied from 0.12 to 0.70 t_C/t_C, excluding values considered outliers (further than 1.5 times standard deviation from mean), while the mean values ranged from 0.17 to 0.52 t_C/t_C, depending on the time horizon and the societal decarbonization scenario (Figure 2). The values between each time horizon and DF decarbonization scenario (i.e., all nine populations) were all statistically significantly different from each other ($p = 0$, using two-sample t-tests). The decarbonization of society reduced the substitution effects, especially in the long term. This led to a greater relative effect of carbon sequestration into the technosphere and to less total variation of the TCCs in absolute terms.

3.3 | Effect of End-Of-Life Options on TCCs

Deployment of end-of-life options that significantly increase the HWP net removal (through BECCS and biochar) has the largest carbon sequestration potential (Table 1). Carbon capture and storage at the end of life of an HWP result in long-lasting carbon removal regardless of the lifespan of the HWP. The maximum theoretical credits based on the highest substitution effect and HWP removal were achieved by producing sawnwood combined with BECCS end-of-life use to the extent possible, or by producing BECCS directly from the roundwood, depending on the decarbonization scenarios and the timescales considered (Table S7, Figure 1). See Table S1 for more details about the performance of the wood products on different time horizons and alternative decarbonization scenarios.

Total TCCs gained by the end-of-life use ranged from 0 to 0.1 t_C/t_C for both heat and power and biofuel and were around 0.4 t_C/t_C for BECCS and 0.2 t_C/t_C for biochar, with assumptions on the development of DFs influencing the results (Table 1). The number

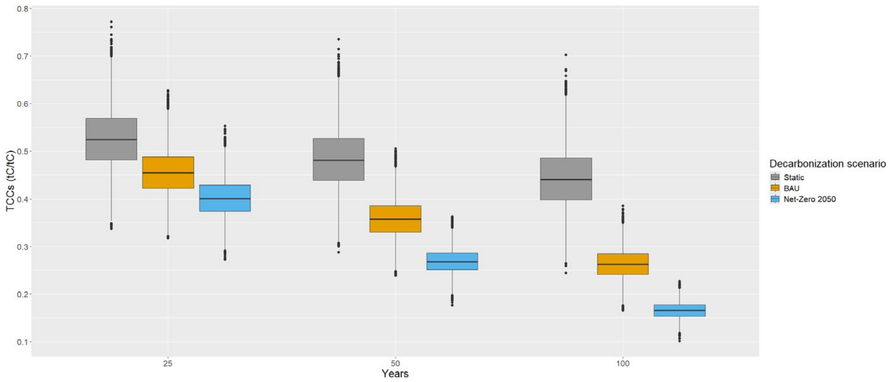

FIGURE 2 | Cumulative technosphere carbon credits per harvested carbon, with three time horizons (25, 50, and 100 years) and three decarbonization scenarios (i.e., DF developments; static, BAU, and net zero 2050), based on the production structure of Finnish forest industry in the Year 2022. The horizontal center line represents the median, the box represents the values between first and third quartiles (including 50% of all values), the whiskers represent ±1.5 times standard deviation, and the dots are values considered outliers. See definition for decarbonization scenarios in Section 2.4.

TABLE 1 | Mean technosphere carbon credits, substitution, and carbon storage in harvested wood (t_C/t_C) cumulated over 100 years given different end-of-life options of wood, assuming the production structure of Finnish forest industry. The default harvest assortments and product allocations are assumed to remain unchanged over the simulation period, and the results reflect the effect of end-of-life use on the total technosphere carbon credits per harvested carbon, when all discarded wood products are directed to the given end-of-life use.

End-of-life option	Decarbonization scenario								
	Static	BAU	Net zero 2050	Static	BAU	Net zero 2050	Static	BAU	Net zero 2050
	Substitution (t_C/t_C)			Carbon storage (t_C/t_C)			TCCs (t_C/t_C)		
No EOL use	0.32	0.16	0.07	0.10	0.10	0.10	0.41	0.25	0.16
Heat and Power	0.39	0.19	0.08	0.10	0.10	0.10	0.49	0.28	0.17
Biofuel	0.39	0.18	0.07	0.10	0.10	0.10	0.48	0.28	0.17
Biochar	0.33	0.16	0.07	0.28	0.28	0.28	0.61	0.45	0.35
BECCS	0.38	0.18	0.07	0.46	0.46	0.46	0.85	0.65	0.54

of TCCs gained from end-of-life options that increase the carbon storage (BECCS, biochar) suffered less from decreasing DFs, and their relative importance in TCCs of wood use increased with decarbonization of society (Table S4).

3.4 | Sensitivity of the Results to the Uncertainty of Input Parameters

The total cumulative TCCs were most sensitive (> 0.1 Spearman ρ) to the 13 parameters (Table 2). Generally, the most influential parameters were the DFs of sawn wood, chemical pulp, mechanical- and semichemical pulp, and energy uses (heat and power and household heat). The substitution rates of sawn wood, chemical pulp, and mechanical- and semichemical pulp were also influential to total TCCs. The influence of half-life of sawn wood increased when assuming societal decarbonization, as it was the most influential parameter assuming net zero 2050 scenario and the third most influential parameter in BAU scenario while being only the ninth most influential parameter in the static scenario. Generally, when assuming increasing decarbonization, the influence of parameters related to substitution decreased, while the influence of parameters related to carbon sequestration increased. Uncertainty of the other input parameters had insignificant impact on the TCCs, regardless of the timescale or the decarbonization scenario (Table S8).

4 | Discussion

4.1 | Comparison of Baseline Results With Other Studies

The mean values for DFs in our default simulations were between 0.07 and 0.34 t of fossil carbon avoided per ton of biogenic carbon contained in wood harvested, considering all time horizons and decarbonization scenarios (see Table S3). The values varied between 0.03 t_C/t_C and 0.61 t_C/t_C, and the average of all values was 0.23. This average value is lower than an average of 0.55 t_C/t_C (range 0.27–1.16 t_C/t_C) reported in a global meta-analysis covering mostly boreal regions such as Scandinavian countries (Hurmekoski et al. 2021). We expect that this is due to the higher level of detail in the study at hand, such as the consideration of the number of functions of intermediate wood products, as well as key assumptions such as the rate of substitution and the rate of decarbonization (see Table S5). These have a strong impact on the results but have mostly been ignored in previous studies (Hurmekoski et al. 2021). The difference may also partly arise from region-specific attributes such as the energy grid, which in Finland is comparatively fossil free, although most of the products produced in Finland are exported globally.

In this study, we used established methods and default assumptions for the HWP net removal calculations. Thus, our default simulation results for HWP net removal over 25 years (0.19 t_C/t_C, Table S3) are well in line with the finding of Zhang et al. (2020) that less than 17% of the carbon harvested from forest remains in the HWP carbon stock over a quarter of a century. This is because currently, approximately 40% of the industrial roundwood globally harvested ends up in material uses, with the rest going to direct energy use (Lauri et al. 2017). However, due to the reduced substitution effects, the scale of substitution effect roughly equals the scale of biogenic carbon stock change already in the BAU scenario with moderate decarbonization efforts.

TABLE 2 | Spearman correlation coefficient of most influential parameters for technosphere carbon credits cumulated over 100 years. The five most influential parameter values per each decarbonization scenario are bolded.

	Spearman correlation coefficient (ρ) for cumulative technosphere carbon credits		
	Societal decarbonization scenario		
Parameter	**Static**	**BAU**	**NetZero2050**
Sawn wood DF	**0.66**	**0.61**	**0.49**
Chemical pulp DF	**0.41**	**0.38**	**0.33**
Mechanical- and semichemical pulp DF	**0.27**	**0.26**	**0.19**
Heat and power DF	**0.27**	**0.25**	0.17
Household heat DF	0.15	0.15	0.12
Sawn wood substitution rate	**0.21**	0.19	0.16
Chemical pulp substitution rate	0.18	0.18	0.14
Mechanical- and semichemical pulp substitution rate	0.11	0.10	0.12
Carbon content of wood products	0.15	0.16	**0.20**
Half-life of sawn wood	0.14	**0.29**	**0.61**
Density of sawn- and roundwood	0.11	0.14	0.15
Percentage of sawn wood to end-of-life use	0.13	0.10	0.04
Yield of sawn wood	0.07	0.11	0.12

4.2 | Comparing TCCs to Forest Carbon Debits

As TCCs are always generated between two different forest harvest scenarios (Cowie et al. 2021; Koponen et al. 2018), the results are not comparable to absolute emissions or removals. We assumed that annual wood demand increased by 1 unit (ton of carbon contained in wood harvest). This implicitly means that in the reference scenario, the annual wood demand is not increased by the studied 1 unit of carbon. Thus, TCCs represent the credits generated in comparison to the reference scenario in which the forests are harvested less than in the studied scenario.

To mitigate climate change, TCCs must be higher than forest carbon debits. However, given all our basic assumptions and all parameter values, the TCCs probably remain considerably lower than forest carbon debits in 25-, 50-, and 100-year time horizons. While simulation of forest ecosystem carbon flows was outside the scope of this study, a recent review paper (Soimakallio et al. 2022) concluded that on average 1 additional unit of carbon harvested each year from forest reduces forest carbon stock on average by 1.43 (SD 0.61), 1.95 (SD 1.21), and 1.41 (SD 0.80) units each year over 25, 50, and 100 years, respectively, compared to a reference scenario without additional harvesting. This can be compared to a range of 0.30–0.70, 0.20–0.65, and 0.12–0.62 t_C/t_C for the TCCs in our study over 25, 50, and 100 years, respectively. Indeed, most previous studies indicate net increase in emissions following a marginal increase in forest harvesting in the European Union (Jonsson et al. 2021), Japan (Matsumoto et al. 2016), Sweden (Gustavsson et al. 2017; Schulte et al. 2022), Canada (Smyth et al. 2014), France (Valade et al. 2018), Switzerland (Werner et al. 2010), Austria (Braun et al. 2016), and Finland (Heinonen et al. 2017; Hurmekoski et al. 2023; Soimakallio et al. 2016). A minority of studies concluding the opposite (Gregor et al. 2024; Petersson et al. 2022) have tended to use a very high single average DF value with few explicit assumptions supporting the analyses.

4.3 | Increasing TCCs

It could be possible to increase the average climate benefit of wood use to some extent without additional harvesting through changes in product portfolios or alternative end-of-life regimes (Brunet-Navarro et al. 2021; Chen et al. 2018; Hurmekoski et al. 2020). In this study, the greatest theoretical potential for increasing the average TCC of wood use was found to relate to shifting by-product use from internal energy to particle board and end-of-life use from landfilling to BECCS, to the extent possible. We show that the carbon sequestration rate per harvested unit can be doubled by applying BECCS or biochar at the end of life of HWPs (Table 1). Both options are currently marginal worldwide, but they have a global potential of 0.5–2 Gt CO_2yr^{-1} and 2–4 Gt CO_2yr^{-1} for BECCS and biochar in 2050, respectively, representing approximately 5%–15% of the current global CO_2 emissions (Fuss et al. 2018). In Finland, biochar is produced to very limited extent, and while BECCS is not currently applied, its potential in Finland has been approximated to be 4–6.9 Mt. CO_2yr^{-1} by 2035 (Kujanpää et al. 2023). However, the scale of application of these technologies depends strongly on how climate policies, their cost-efficiency, and social acceptability develop.

There are several constraints on the ability to improve the average TCC. Firstly, there are physical or technoeconomic constraints such as the log–pulpwood ratio which can only be changed to some extent within the overall yield expectations through forest management (Tahvonen et al. 2010), and the amount of lignin that can be extracted from black liquor to still enable internal energy production in pulp mills without shifting to an entirely different energy system. Secondly, the market is naturally governed by both supply and demand. If the production structure changes in one region, the supply structure is likely to change in other regions to cover the gap in demand (Kallio et al. 2018; Pan et al. 2020). However, if the supply of wood products changes globally, this should have secondary and tertiary consequences on the supply and demand of closely related materials. Thus, both the regional and global net effects of changes in the supply structure in one region remain still highly uncertain (Pan et al. 2020).

Cascading use of wood (reuse, recycling, or downcycling of HWPs before eventual energy recovery) could also possibly increase TCCs (Budzinski, Bezama, and Thrän 2020). We implicitly included these aspects only to some extent in our uncertainty ranges applied for the lifespan of HWPs and DFs. In some cases, it is possible to reduce production emissions of HWPs, lengthen lifespan of carbon sequestered in HWPs, or decrease the demand for virgin wood. However, the anticipated effect strongly depends on the case-specific assumptions, such as which materials were primarily substituted by wood products, the recyclability of the substituted materials, functional equivalency of recycled materials, and the emissions of the recycling processes.

While feedstock substitution may play a role in sustainability transformations, the results of this study clearly indicate that it is not a silver bullet in addressing the environmental burdens caused by overconsumption. The issue is exaggerated by imperfect substitution, implying that an increase in the use of wood may not only substitute alternative materials but also partly increase the overall material use of the economy. Thus, apart from product and process innovations, socioeconomic innovations are required to, for example, increase the lifetime of products (Moazzem et al. 2021) and to minimize unnecessary purchases (Wiedemann et al. 2023).

4.4 | Geographical Scope

The data used for determining the TCCs were specific to the wood-based products and energy produced in Finland and consumed globally. The location of consumption affects the energy DFs, which were based on global values for the end-of-life stage, but Finnish values for the production stage, due to the different energy grids. For material uses, the DFs were based on European averages, as the majority of the products produced in Finland are exported to the European Union. However, a more detailed analysis of trade flows would be too demanding, and would not improve the analysis, as the substituted products may be produced in third countries, which would require another layer of uncertain assumptions. The purpose of our study was not to track certain wood flows in detail, but rather to assess the uncertainty ranges considering various sources of uncertainty.

Overall, important differences exist between countries in material flows, markets, and unit emissions, for example. Firstly, energy mixes play a major role in determining the WNDFs. Most of the energy use in sawn wood and pulpwood mills in Nordic countries such as Finland or Sweden is covered by the by-products of wood processing, which may not be the case in continental Europe or globally, where a larger portion is used for wood-based panels, for example, or it goes into waste. This could reduce the average WNDFs compared to our results. Conversely, the energy mix in these Nordic countries has a relatively low proportion of fossil fuels, leading to lower WNDFs for direct energy use in this region compared to the rest of the world. Secondly, the product mix and the substituted functions may differ between regions even within this Nordic zone, but more radically when compared to deciduous plantation forests in the tropical or subtropical zones. However, while the products and substitution cases may be different, the substitution effects may not necessarily differ radically given the relatively limited variation in WNDFs across all identified wood uses. The same holds true for potential new wood-based products, which cannot cause much lower fossil emissions compared to the current products relying mostly on bioenergy (counted as zero emission). An exception can be efficiency gains of integrated production facilities as compared to geographically more extensively distributed value chains, for example, in case of producing textiles (Shen, Worrell, and Patel 2010). Moreover, the variation in substitution effects decreases more, the faster the decarbonization of the energy sector.

4.5 | Limitations

The estimation of substitution effects requires compromises between the coverage of the system boundary and the level of detail for the underlying data. Our work covered all wood uses, albeit with major data gaps. This could be described as a supply-oriented approach, as it traces the major end-use sectors of intermediate wood-based products (Schulte 2024). We further aimed to address the uncertainty in the substitution assumptions via systematic sensitivity analysis, but this also remains conditional on the initial data and the estimated range of uncertainty. An increased number of comparative life cycle assessments particularly on the various end uses of solid wood products and pulp and paper products could alleviate this uncertainty. However, we cannot see that this would change the overall conclusions of our study.

Another approach would be to focus on a single sector at a time to have access to representative life cycle inventory and life cycle assessment data (Hafner and Rüter 2018). While a more demand-oriented approach tracing the amounts of wood-based products required to produce a certain type and number of functional units would result in more accurate estimates, it could reasonably only be applied to a restricted case with an arbitrary system boundary ignoring, for example, the interconnected feedstock supply and demand of wood uses. Regardless of the approach, assumptions play a decisive role in the estimation of substitution impacts, as substitution cannot be directly measured or verified. It only occurs relative to a hypothetical counterfactual development that will never exist if the studied scenario is realized.

Due to the wide system boundary, the product comparisons in each identified substitution case were conducted at the level of intermediate products (e.g., sawnwood and concrete used in a roof element) instead of end-use functions (e.g., a more wood-intensive and less wood-intensive building). The latter would result in more realistic analyses, as the end uses would be connected to actual volumes of consumed end-use functions. Significantly increasing the volume of wood used in roof elements would be highly misleading, given that both wood-framed and non–wood-framed buildings typically use wooden roof elements (Sathre and O'Connor 2010), so such a scenario would violate mass balance rules, as no or little additional substitution can occur in this segment (Rüter et al. 2016). However, one can still argue that substitution has occurred in the baseline because it appears unlikely that a building would not have been built or a building would have been built without a roof if wood was not used to provide this function. Thus, the current model should be applied very carefully, if adopted for the purpose of examining structural changes in wood uses, keeping certain functions fixed while making more detailed assumptions and scenarios for the functions of interest, such as certain building types (Hurmekoski et al. 2023).

Despite the streamlined substitution modelling approach, the presented ranges for the DFs ought to capture a lot of the variation at the level of end uses. For example, coniferous sawnwood used in walls replacing concrete and bricks avoided an average of 0.80 tC/tC, with a range of 0.50–1.60 tC/tC (S4). This compares to an average of 0.60 tC/tC, with a range of 0.12–1.89 tC/tC in above 30 recent comparative LCA estimates for residential-detached and semi-detached buildings (Hafner and Rüter 2018; Hafner and Schäfer 2017; Hafner and Özdemir 2022). While there are several comparative LCA estimates allowing calculation of building-level DFs, the coverage of life cycle inventory and market data remains poor, so a full calibration of the model is not possible.

4.6 | Concluding Remarks

Our results indicated that TCCs of wood use are uncertain due to a large range of uncertainty across the parameters influencing the TCCs. The TCCs of wood use could be increased by directing wood into construction materials, increasing the lifespan of HWPs in use, and avoiding emitting carbon into the atmosphere at the end of life of the HWPs. However, the anticipated decarbonization of societies will reduce the substitution effects significantly over time—lower fossil-based emissions translate into lower potential for additional avoided fossil-based emissions. Thus, the TCCs are very likely lower than the forest carbon debits resulting from additional tree harvesting. This implies that additional harvesting of wood increases net GHG emissions into the atmosphere. Our results are valid at least under Nordic conditions, but the identified challenges related to magnitudes and uncertainties of TCCs can be expected to be similar for many other regions. Enhanced regional-specific data would be required to extend the applicability of the results to a global level. Our results emphasize the need to reduce overall consumption and increase the recycling of both wood and non-wood products to mitigate climate change.

Author Contributions

Jari Niemi: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, supervision, visualization, writing – original draft, writing – review and editing. **Sampo Soimakallio:** conceptualization, data curation, funding acquisition, methodology, resources, writing – original draft, writing – review and editing. **Elias Hurmekoski:** data curation, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Tanja Myllyviita:** visualization, writing – original draft, writing – review and editing. **Janni Kunttu:** data curation, investigation, writing – original draft, writing – review and editing. **Federico

Lingua: writing – original draft, writing – review and editing. **Tord Snäll:** writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/records/14514372.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.