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Climate Change Mitigation Challenge for Wood Utilization—The Case of Finland

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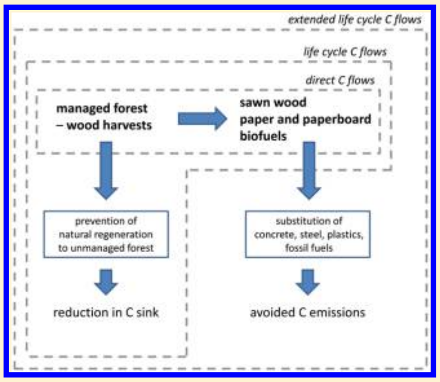
S *Supporting Information*

ABSTRACT: The urgent need to mitigate climate change invokes both opportunities and challenges for forest biomass utilization. Fossil fuels can be substituted by using wood products in place of alternative materials and energy, but wood harvesting reduces forest carbon sink and processing of wood products requires material and energy inputs. We assessed the extended life cycle carbon emissions considering substitution impacts for various wood utilization scenarios over 100 years from 2010 onward for Finland. The scenarios were based on various but constant wood utilization structures reflecting current and anticipated mix of wood utilization activities. We applied stochastic simulation to deal with the uncertainty in a number of input variables required. According to our analysis, the wood utilization decrease net carbon emissions with a probability lower than 40% for each of the studied scenarios. Furthermore, large emission reductions were exceptionally unlikely. The uncertainty of the results were influenced clearly the most by the reduction in the forest carbon sink. There is a significant trade-off between avoiding emissions through fossil fuel substitution and reduction in forest carbon sink due to wood harvesting. This creates a major challenge for forest management practices and wood utilization activities in responding to ambitious climate change mitigation targets.



1. INTRODUCTION

Finland is a northern country with a forest-dominated landscape: its boreal forests cover about 22.8 million hectares of the land area of 30.4 million hectares, forest land area corresponding to 14% of that in the EU28.[1] Around 90% of the Finnish forests are even-aged, predominantly coniferous managed forests and classified as seminatural.[2] In 2010, the mean growing stock volume was lower in Finland (100 m^3/ha) compared to the average Europe (111 m3/ha), EU28 (153 m3/ha), North and Central America (123 m3/ha), U.S. (155 m3/ha) or global (131 m3/ha) levels.[1] This is explained by the climate, geography and soil characteristics together with the forest management history. Contrary to average European forests that are increasingly mature,[3] Finnish forests are relatively young and in well-growing age.[1] In Finland, the share of fellings to net annual increment was at the average EU28 level while the absolute fellings and net annual increment were one of the highest in the EU28 in 2010.[2]

Forest growth has exceeded wood removals for decades in Finland. Between 1990 and 2012, the annual national net CO_2 sink of Finnish forest land varied approximately between 20 and 50 Mt CO_2, including living biomass, soil organic matter and dead organic matter. The fluctuation was mainly due to changes in commercial roundwood fellings (typically 50–60 Mm^3 in the 2000s), affected by the international market of forest industry products.[1] In Finland, the share of forest products of the value of total exports was the largest in the world in 2013 (20%), coming mainly from pulp and paper industries.[1] Out of the global production, 3% of sawn softwood, 6% of wood pulp, and 3% of paper and paperboard were produced in Finland in 2013.[1] In the Finnish energy supply, wood fuels, especially black liquor, also have a large role, accounting for one-fifth of the annual total energy consumption in 2010.[1]

The bioeconomy has been emphasized as a means of achieving a sustainable society in Finland, as in the whole of EU28.[4] Considering the structure of the Finnish forests, Finland could supply a remarkable share of the pursued wood utilization increase in the EU28 required for the transition to the bioeconomy. At the same time, countries worldwide aim to limit global surface warming to well below 2 °C compared to the preindustrial level[5] requiring the global net greenhouse gas (GHG) emissions to be cut down to zero within the upcoming decades and even further reduced to negative by the end of the century.[6] This poses challenges for the intended transition to bioeconomy. *First*, the majority of carbon (C) harvested from forests is released within a few years after harvesting due to

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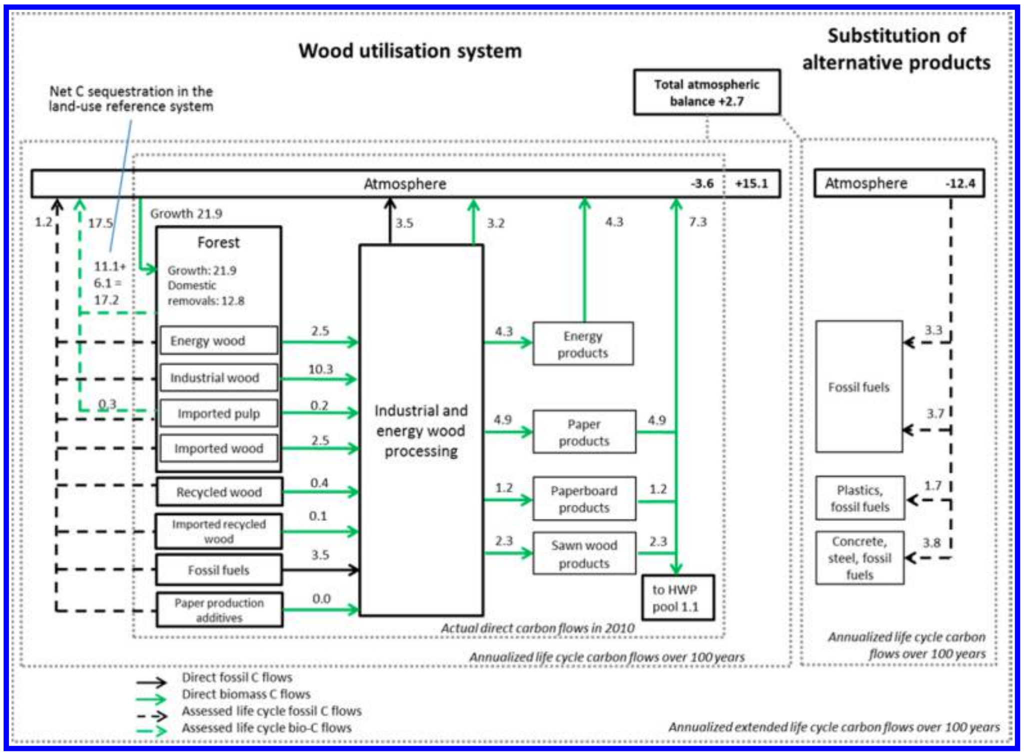

Figure 1. Actual direct carbon (C) flows of wood utilization in Finland in 2010 and annualized life cycle and extended life cycle C flows over 100 years for a scenario relying on 2010 wood utilization structure (all C flows expressed in Mt Cyr^{-1}). Life cycle C flows include the direct C flows presented in the inner system boundary, and extended life cycle C flows include the life cycle C flows. Forest carbon sink in the land-use reference system in comparison to wood utilization system is analogous to a carbon emission into the atmosphere. Mean values were applied for the stochastic variables.

energy use or decay.[7] *Second*, regardless of whether forest C stock is increasing (such as in Finland) or nearly stable (like in forests in natural state), wood harvesting immediately reduces forest C stock in comparison to no (or less) harvesting.[8] This reduction is a negative sink effect related to wood harvesting, and it may take from decades to centuries until it is fully paid back.[9] *Third*, harvesting and processing of forest biomass requires energy and other auxiliary inputs such as chemicals, which are partly based on fossil fuels.[10,11] On the other hand, harvested wood products can substitute fossil fuels either through material or energy use, and in some cases through both material and energy use.[12] The overall displacement effect depends on the life cycle GHG emissions of fossil fuels substituted as well as wood products produced, thus it is highly case-specific.[12−14]

Typically, the studies of climate impacts of wood utilization have focused on wood removals for bioenergy[15] or case-specific uses of wood materials in construction,[13] while disregarding the impacts of pulp and paper industry.[14] However, saw log, pulpwood and energy wood availability and utilization are tightly interconnected: sawmilling residues are used as a feedstock in pulping; saw logs and pulpwood are concurrently extracted from forests in harvest operations; and furthermore, forest and industrial residues for energy utilization become available only through industrial wood use.[16,17] Only a limited number of studies have taken these interactions into account when considering the climate impacts of wood utilization (e.g., refs 18 and 19). In addition, the sensitivity of the results to the parameter uncertainties have often been overlooked.[11]

The aim of this paper is to comprehensively examine the net carbon emissions associated with wood utilization in Finland. Another aim is to comprehensively consider the sensitivity of the results to the parameter uncertainties. We study the annual life cycle carbon emissions in several constant wood utilization scenarios over 100 years from 2010 onward. Altogether six different scenarios are considered: the continuation of 2010 wood utilization structure (consisting of various activities), and the hypothetic immediate introduction of five different wood utilization structures presented for 2050 based on different storylines on economic growth, technological development, GHG emission reduction target and wood demand.[20] Finally, we pay attention to and critically discuss our most important assumptions and elaborate on the challenges forest management and wood utilization encounter in urgent climate change mitigation.

2. METHODS AND MATERIALS

2.1. System Description. The studied technosphere included the carbon flows related to the wood utilization system in Finland (see Figure 1). In addition to *direct carbon emissions*, we take into account embodied carbon emissions including changes in forest carbon sink (referred as *life cycle carbon emissions*), and furthermore the avoided carbon emissions from displacement of alternative materials and energy by harvested wood products (referred as *extended life cycle carbon emissions*). The temporal scope of wood utilization scenarios was 100 years (from 2010 onward) based on three essential arguments. *First*, wood harvesting influences dynamically the forest carbon stock why it is difficult to separate the impacts of one-time wood harvesting from subsequent forest management activities taking place within the studied time horizon.[21] Immediately, forest carbon stock is reduced by the

Table 1. Overall Wood Input and Material and Energy Output in the Wood Utilization Scenarios Studied

wood flows in finland	2010	base	constant	save	stagnation	change
wood input as roundwood (including imports), Mm^3	77.0	91.6	100.5	106.4	91.2	92.9
external energy input (other than wood), TJ	138 839	150 401	157 091	132 999	105 124	97 042
material output, Mm^3	10.8	12.2	16.0	16.6	13.6	11.7
- new products including biocomposites	0.0	0.1	4.0	2.0	0.5	5.2
- plywood	1.0	1.5	1.1	1.1	1.1	0.9
- fiber and particle board	0.3	0.1	0.1	0.1	0.1	0.1
- sawn wood	9.5	10.5	10.8	13.4	11.9	5.5
material output, Mt	14.7	16.1	13.3	13.4	9.3	9.6
- paper production	8.9	8.0	3.2	4.4	3.2	2.1
- paperboard production	2.8	3.9	2.6	3.0	2.3	2.0
- exported wood pulp converted into paper	2.9	3.9	4.8	5.1	3.5	2.4
- dissolving and fluff pulp, new fiber products	0.0	0.3	2.7	0.9	0.3	3.1
energy output, TJ	145 017	160 439	199 314	226 251	224 251	225 314
- fuelwood and wood residues for small-scale housing	63 377	28 251	28 251	28 251	28 251	28 251
- fuelwood and wood residues for heat and power production	77 000	90 188	104 063	111 000	111 000	104 063
- liquid biofuels	0	42 000	67 000	87 000	85 000	93 000
- wood pellets	4 640	0	0	0	0	0

respective carbon content of the wood harvested in comparison to no harvesting.[9] In the longer run, the impact becomes dynamic and it is determined as the difference in the forest C stock development between the wood harvesting and "no-harvest" scenario.[9] *Second*, considering the requirements of ambitious climate change mitigation targets, variations in annual GHG emissions are not as important as the cumulative emissions over the upcoming 100 years.[22] *Third*, structural and strategic decisions in forest management or climate change mitigation are related to a regular or continuous supply of a given function (e.g., wood utilization) instead of occasional decisions relying on a one-time fulfilment of a function (e.g., annual wood utilization).[23]

We assumed that the wood utilization structures considered in the scenarios were available immediately and remained constant over the studied 100-year time horizon. Thus, we did not consider the time required to develop and commercialize new technologies and to introduce a certain new wood utilization structure. We considered all the wood processed for intermediate or final products in Finland. This means that we included domestic use of harvested or imported roundwood, forest residues, recycled wood and imported pulp, but excluded roundwood exports which correspond only to 1−2% of the domestic wood consumption.[1] We considered imported wood as it would have been harvested from the Finnish forests. In addition, we assumed that exported pulp is converted into paper.

2.2. Methods. We used substance flow analysis (SFA) as a method to track and quantify the direct carbon flows in the system under study.[24] When modeling the life cycle carbon emissions of the wood utilization system as *it is* within the given temporal window, we followed the principle of attributional life cycle assessment (ALCA).[25,26] The functional unit chosen was harvested wood (t C). In order to model the carbon impacts of the studied wood utilization system, we separated the respective technosphere from the ecosphere. This was done using a no-human-intervention land-use reference system within the studied temporal window,[27−29] here reflecting no-harvest of forest over the studied 100-year time horizon. To quantify the forest C sink impacts, we applied the relative carbon (RC) indicator introduced by Pingoud et al.[9] over a 100-year time horizon (RC_{100}). The indicator describes cumulative reduction in the forest carbon sink per the amount of carbon harvested from forest, both over the given time horizon.

We compared the life cycle carbon emissions of a wood utilization system to those of alternative materials and energy, serving equivalent (comparable) function with harvested wood products. By deducting the life cycle carbon emissions of alternative products from those of wood utilization system, it is possible to consider an extended carbon balance. The balance describes how efficiently, in theory, the overall wood utilization system in Finland functions in climate change mitigation. In this system expansion,[30] the avoided life cycle carbon emissions of alternative products are considered as "substitution credits" of the wood utilization system. We assumed that the substitution is perfect, implying that the total amount of consumption of goods does not change in response to the production of goods.[31] We considered "substitution credits" from material and energy use of wood when available. For functions served by traditional paper products, we assumed that there are no functionally equivalent products to be substituted. However, we assumed that traditional paper products are recovered and used as energy at the end of their life cycle, thus achieving "substitution credits" from energy use.

First, we calculate the results deterministically using mean values determined for each of the variables. Second, we studied the uncertainty and sensitivity of the results to the input parameter uncertainties using the Monte Carlo simulation. It is a method in which a probabilistic analogy is used to solve deterministic problems of uncertainty. It performs a deterministic computation of the input parameters for a selected number of the samples (here 10,000) from each probability distribution. Then, it aggregates the samples as probability distributions. To characterize the probabilities (P), we used the IPCC terminology:[6] virtually certain refers to 99−100%, very likely to 90−100%, likely to 66−100%, about as likely as not to 33−66%, unlikely to 0−33%, very unlikely to 0−10%, and exceptionally unlikely to 0−1% probability, respectively. To measure the contribution of a single variable to the uncertainty of the carbon emissions, we used Spearman's rank correlations (ρ) between each of the variables and the result values (see Supporting Information (SI) SI2 for more information). We used MS Excel software and its add-in @Risk application to carry out all the calculations.

Table 2. Parameter Assumptions Used in the Model and the Spearman'S Rank Correlations (ρ) between Each of the Variables and the Result Values (Ranges Show the Variation in the Scenarios Studied); in Case a Stochastic Input Variable Not Applied for a Studied Scenario, Referred As "Na" (Not Available); see SI SI1, 2 for More Details

stochastic input variables	unit	2.5%:ile	mean	97.5%:ile	ρ
average dry-fresh density of wood	t/m^3	0.40	0.42	0.44	0.0
lower heating value (LHV) of solid wood fuels in heating and power plants	GJ/m^3	6.2	6.9	7.6	0.0
lower heating value (LHV) of solid wood fuels in small-scale housing	GJ/m^3	8.5	9.4	10.4	0.0
lower heating value (LHV) of wood pellets	GJ/t	14.4	16.0	17.6	0.0, na
C sequestration into harvested wood product (HWP) pool in 2010	t_C/yr	0.5	1.1	1.6	0.0
reduction in the forest carbon (C) sink per the C content of wood harvested over 100 years (RC_{100})	t_C/t_C	0.4	0.7	1.1	0.9
round wood requirement in chemical pulping	m^3/m^3	1.8	2.5	3.3	0.0
round wood requirement in mechanical pulping	m^3/m^3	0.8	1.2	1.6	0.0
CO_2 emissions from fuel consumption in wood harvesting	kg_{CO2}/m^3	3.7	5.3	6.9	0.0
CO_2 emissions from natural gas combustion	t_{CO2}/PJ	52.3	55.0	57.8	0.0, na
CO_2 emissions from peat combustion	t_{CO2}/PJ	100.7	106.0	111.3	0.0, na
CO_2 emissions from heavy fuel oil combustion	t_{CO2}/PJ	75.1	79.0	83.0	0.0, na
CO_2 emissions from coal combustion	t_{CO2}/PJ	88.4	93.0	97.7	0.0, na
CO_2 emissions from other fuel (REFs, liquefied petroleum gas and other biofuels) combustion	t_{CO2}/PJ	22.3	31.8	41.3	0.0, na
CO_2 emissions from wood combustion	t_{CO2}/PJ	104.1	109.6	115.1	0.0
CO_2 emissions from production of consumed electricity (net purchase) in 2010 structure	t_{CO2}/PJ	49.0	70.0	91.0	0.0−0.1, na
CO_2 emissions from production of consumed heat (net purchase) in 2010 structure	t_{CO2}/PJ	66.5	95.0	123.5	0.1, na
the share of fossil fuel upstream CO_2 emissions from the combustion emissions		0.05	0.13	0.2	0.0
energy consumption of converting exported pulp to paper	t_{CO2}/t	0.5	0.75	1.0	0.0
CO_2 emissions embodied in pulp and paper industry imports	t_{CO2}/t	0.1	0.2	0.3	0.0
C content of sawn wood products and wood pulp	t_C/t	0.48	0.5	0.52	0.0
C content of paper and paperboard products	t_C/t	0.38	0.41	0.45	−0.1−0.0
substitution factor for sawn wood and wood-based panels (concrete, steel substitution)	t_C/t_C	0.5	1.3	2.0	−0.3-(−0.2)
substitution factor for paper products (fossil fuel substitution)	t_C/t_C	0.5	0.8	1.0	−0.2-(−0.1)
substitution factor for paperboard products (plastics, fossil fuel substitution)	t_C/t_C	0.5	1.4	2.4	−0.2-(−0.1)
substitution factor for energy and postused mechanical wood products (fossil fuel substitution)	t_C/t_C	0.5	0.8	1.0	−0.3-(−0.2)
the share of fossil fuels in total fuel consumption of forest industry in 2050 structures		0.2	0.25	0.3	0.0, na
CO_2 emissions from fossil fuel combustion in 2050 structures	t_{CO2}/PJ	52.3	81.8	111.3	0.0−0.1, na
CO_2 emissions from production of consumed electricity (net purchase) in 2050 structures	t_{CO2}/PJ	4.9	25.2	45.5	0.0, na
CO_2 emissions from production of consumed heat (net purchase) in 2050 structures	t_{CO2}/PJ	6.6	34.2	61.7	0.0, na

2.3. Material. The overall wood and external energy inputs and material and energy outputs of the scenarios are presented in Table 1. All the calculation equations and input parameter assumptions with sources are presented transparently in SI SI1. We entitled the six different scenarios relying on various but constant wood utilization structures as '2010', "Base", "Constant growth", "Save", "Stagnation", and "Change". The data for the 2010 structure was derived from the statistics.[32−34] The data for the other five structures studied are those presented for the year 2050 in the energy and climate roadmap for Finland.[20,35−37] These future structures are based on different storylines continuing the current climate policy in the EU and Finland ("Base") and aiming to reduce the GHG emissions by 80% by 2050 from the level of 1990 ("Constant growth", "Save", "Stagnation", and "Change") (see Kallio et al.[37] and SI SI2 for more details). The wood demand, wood products produced, and GHG emission intensity of the energy inputs vary between the six scenarios studied. To convert the material and energy balances of wood utilization into life cycle carbon balances, we made several assumptions based on literature (Table 2, SI SI1, 2). We set the uncertainty ranges for these assumptions so that the ranges correspond to the uncertainty due to lack of knowledge or variability in case-specific characteristics (technologies, conversion efficiencies etc.) that can be expected to take place in large-scale according to our current knowledge.

3. RESULTS AND DISCUSSION

3.1. Direct Carbon Emissions of the Wood Utilization System in 2010. The direct carbon emissions due to wood utilization in Finland in 2010 were −3.6 Mt C (Figure 1). Thus, the system functioned as a net carbon sink. Net C sequestration into forest biomass exceeded direct C emissions from wood utilization and fossil fuel combustion in industrial and energy wood processing. This held true although a relatively large amount of wood was imported from abroad into the system and over 90% of the carbon transferred from the forest to harvested wood products was released into the atmosphere.

3.2. Life Cycle Carbon Emissions of the Wood Utilization System in the 2010 Scenario over 100 Years. Extension of the direct carbon flows to life cycle carbon flows changed the atmospheric C emissions significantly, from an actual net sink to a source in comparison to the reference system. Life cycle carbon emissions calculated using mean values corresponded to +15.1 Mt C annually for 2010 wood utilization scenario over 100 years (Figure 1). The 18.6 Mt C difference between annual direct and annualized life cycle flows consisted of three factors. First, the fossil C emissions embodied in fossil fuels, paper production additives, and imported wood increased the carbon flow to the atmosphere by 1.2 Mt C. Second, imported pulp involved embodied biogenic carbon emissions (0.3 Mt C). Third, and most importantly, when accounting for life cycle carbon flows, continuous wood harvesting over the studied 100-year time horizon resulted in

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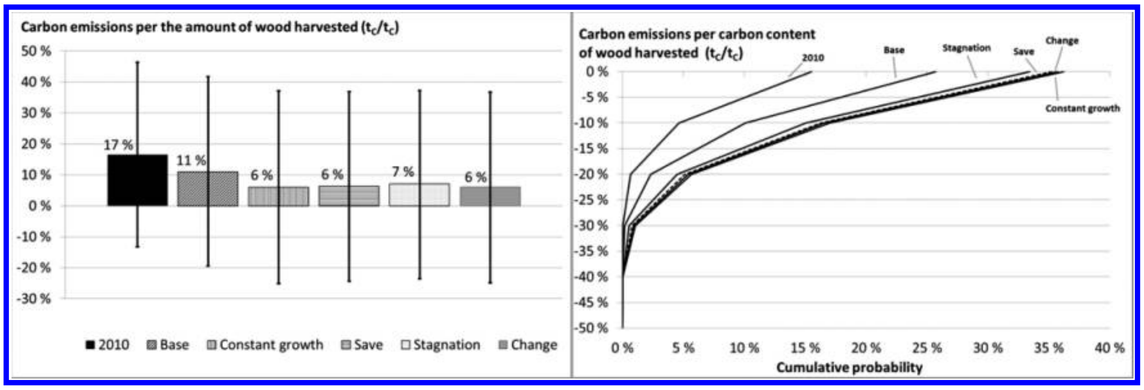

Figure 2. Extended life cycle carbon emissions per wood harvested (t_C/t_C) in all the studied scenarios (include avoided emissions from substitution of alternative materials and energy products); left: mean values (bars and labels) and central 95% confidence interval (error bars), and right: cumulative probabilities for negative carbon emissions indicating emission reductions.

smaller forest C stock compared to the land-use reference system with no wood harvesting. This forest C sink reduction is analogical and considered as an emission in the life cycle balance. Annual round wood harvesting including imports equaled 15.8 Mt C (2.5 + 10.3 + 0.2 + 0.3 + 2.5 in Figure 1) which resulted in annual reduction of 11.1 Mt C in the forest carbon sink over the studied time horizon. As annual forest growth exceeded domestic and foreign removals, 6.1 Mt C (21.9−12.8−2.5−0.2−0.3 in Figure 1) was sequestered in forest in the wood utilization scenario. In order to describe the 11.1 Mt C (15.8 * 0.7) reduction in forest C sink appropriately, the net C flow to the atmosphere was accounted as 17.2 Mt C (11.1 + 6.1) in the reference land-use system (Figure 1). This way the overall life cycle C emissions equaled the emissions calculated by applying the RC_{100} variable (15.8 × 0.7) (see Section 3.5 and SI SI1, 2).

3.3. Extended Life Cycle Carbon Emissions Including Avoided Emissions in the 2010 Scenario over 100 Years.

Further extension of the system boundary to include the avoided emissions from substitution of alternative materials and energy products reduced significantly the net carbon emissions related to the wood utilization in Finland compared to the life cycle flows. However, the net carbon emissions remained positive over the studied 100-year time horizon, although reduced to 2.7 Mt C yr^{-1} (Figure 1). This was because the substitution credits (−12.4 Mt C yr^{-1}) were not large enough to compensate the combined emissions from the reduction in forest C sink (11.1 Mt C yr^{-1}), fossil fuel inputs (3.5 Mt C yr^{-1}) and other embodied emissions (1.5 Mt C yr^{-1}).

3.4. Extended Life Cycle Emissions for the Six Wood Utilization Scenarios Considering Input Variable Uncertainties.

Estimation of the life cycle C emissions of wood utilization and the emissions avoided through substitution of alternative materials and energy products (extended life cycle C emissions) involved a number of uncertainties. According to the Monte Carlo simulation results, the net carbon emissions (expressed per wood harvested) to the atmosphere likely (or at least about as likely as not) increased in all the scenarios studied (cumulative $P < 40\%$ for emission reductions; Figure 2). Emission reduction of 10% was unlikely, emission reduction of 20% was very unlikely, and further, emission reductions more than 30% were exceptionally unlikely for all the scenarios studied (Figure 2). The results for the scenarios relying on 2050 wood utilization structures indicated a somewhat higher probability for lower carbon emissions compared to the scenario relying on the 2010 structure. This was mainly due to the assumed lower carbon emissions from fossil energy consumption in wood processing in the 2050 structures compared to the 2010 structure (SI SI1).

3.5. Assumptions of the Most Important Parameters.

Calculations based on mean values of the input parameters (Figure 1, SI SI1) indicated that the extended life cycle carbon emissions of wood utilization scenarios studied were mainly determined by the reduction in the forest C sink (increasing the emissions balance) and substitution credits of wood products (reducing the emissions balance). The sensitivity analysis of the stochastic simulations (Table 2, SI SI2) indicated that the uncertainty of the results (Figure 2) was mainly determined by the parameter "*reduction in the forest C sink per the C content of wood harvested* (RC_{100})". The absolute value of Spearman's rank correlation coefficient (ρ) for this particular parameter (around 0.9) was significantly higher than for any other input variable for all the wood utilization scenarios studied (Table 2, SI SI1, 2). Substitution factors influenced the uncertainty of the results with moderate significance (ρ values vary from −0.3 to −0.1). The rest of the parameters had an almost insignificant impact on the uncertainty of the results. In the following, the representativeness of the assumptions used for the most important parameters are considered.

The central 95% confidence interval range for the RC_{100} (*reduction in the forest C sink per the C content of wood harvested*) was defined to vary from 0.4 to 1.1 (Table 2). RC_{100} value of 1, less than 1 or more than 1 indicates that wood harvesting influences forest C sink equally to, less or more than extraction of the same amount of C influences fossil C origin, respectively, over the 100 year time horizon. The analysis based on the forest management scenario studies[17,21] presented in SI showed that RC_{100} in Finland is probably around 1.0−1.2 without stochastic events such as storms, fires and other natural damages. However, as unmanaged forests may pose higher risks for such disturbances[38,39] we reduced the lower limit to 0.4. It should be noted that if shorter time horizons than 100 years (e.g., up to 2050) were applied, significantly higher values for RC (even up to 2−3) due to forgone C sequestration would be posed (SI SI2), resulting in higher net carbon emissions of wood utilization scenarios.

We described *the life cycle carbon emissions of alternative materials and energy products avoided through substitution* (i.e., the "substitution credit") using dimensionless substitution factors (ton fossil carbon avoided per ton biomass carbon embodied in wood product). These factors are subject to significant uncertainties, as it is difficult to know exactly what the alternative products replaced by wood products are. The carbon emissions from alternative *energy* products depend on the fuel and technology. When *bioenergy* replaces the use of fossil fuels, the range for substitution credits likely vary between efficient natural-gas-fired power generation (0.5) and typical coal-fired power and heat production (1.0) systems.[40,41] Consequently, the 95% central confidence interval range applied (0.5−1.0) can be assumed to cover a wide range of functionally equivalent energy production systems (heat, power or in transportation).

We assumed that *paper products* can substitute alternative energy sources at the end of life. Although paper can be recycled as fiber raw material for new paper and paperboard products, energy substitution assumption can be considered reasonable as the fiber can typically be reutilized only a few times,[42] thus ending up rapidly into energy recovery. We assumed that 100% of the paper produced was recovered at the end of life. This is clearly an optimiztic assumption as the recovery rate of paper and paperboard products consumed in Finland was approximately 65% in 2010,[32] and it may be difficult to gain a 100% recovery level in practice. *Paperboard products, dissolving and fluff pulp and new fiber products* may substitute alternative energy products at the end of life cycle, similarly to paper. In addition to energy substitution, these products may be used to substitute plastics in a variety of product systems.[43] When replacing plastics, the energy substitution at the end of life does not provide additional credits given that in an alternative system plastics could have been used for energy as well. Thus, we adopted a range which covers either energy recovery or virgin plastics substitution possibilities for these products.

Multiple alternative products may be used instead of *mechanical wood products*, and it may be difficult to define equivalent functionality between different mechanical wood products and the respective alternatives.[14] Mechanical wood products are mainly used in construction,[44] the most important alternative materials being concrete and steel.[13] However, the amount of alternative materials replaced is case-specific,[13] and the use of wood as construction material typically involves the use of some additional materials, for example due to fire-protection requirements applied in construction.[40] Consequently, for large-scale material substitution it is necessary to analyze functionally equivalent buildings (including operational phase) rather than single materials in single applications.[40]

We applied the central 95% confidence interval range of 0.5−2.0 for the substitution factor for *sawn wood and wood-based panels*. This is representative according to literature. The substitution factors of wood materials have been estimated to equal 0.5 for the Finnish[45] and 1.1 for the Swiss construction sector,[46] respectively. The substitution factors for various building types have been estimated to equal 1.5 for apartment building,[47] 1.9−2.3 for single-family house,[48] and 1.0, 1.5, and 2.3 for warehouse, 3-story building and single-family house, respectively.[49] The meta-analysis by Sathre and O'Connor[13] presents displacement factors of wood product substitution up to 15, but only up to 2.3 for pure material substitution. The substitution factor applied in this paper for sawn wood and wood-based panels should not be confused with those (partly high) displacement factors which include the postuse of wood products and fossil fuel substitution through the use of wood processing or harvesting residues (see Sathre and O'Connor[13]), as we handled these factors separately. In our analysis, the avoided emissions through fossil fuel substitution of using wood processing residues *not used* for wood processing itself were accounted for in energy substitution. Carbon sequestration into the harvested wood product (HWP) pool was defined in accordance with national GHG inventory reporting to the UNFCCC[34] for the 2010 structure, and adjusted with the amount of mechanical wood products produced for the 2050 structures (SI SI1). We assumed that the carbon in mechanical wood products *not* sequestered into the HWP pool was fully used as energy. Thus, the impact of the significant uncertainty related to C sequestration into the HWP pool (Table 2) was mainly compensated by the substitution credits through postuse energy recovery.

3.6. Challenges for Future Research. For wood utilization to be efficient in urgent climate change mitigation, (1) the reduction of the forest carbon sink due to wood harvesting should be minimized, (2) the long-term C stock of wood products should be maximized, and (3) the avoided emissions through substitution should be maximized. In Finland, this would require development and optimization in both forest management practices (rotation periods, thinning intensities, tree species, fertilization etc.) and wood utilization activities (volume, energy efficiency, product palette etc.). It may be difficult to increase the C sequestration into the HWP pool significantly relative to the C harvested from forests. Furthermore, it is not possible to gain significantly higher substitution credits than we assumed for biobased materials or biofuels mainly intended to be used in place of crude-oil-based products. Thus, reaching large emission reductions per wood harvested would require either very high substitution factors for mechanical wood products or a very small reduction in cumulative forest C sink due to wood harvesting (see additional sensitivity analysis in SI SI2), both being unrealistic in large-scale based on our current knowledge. In the long run, high substitution credits could perhaps be possible for a successful introduction of new nanocellulose-based products[43] that could displace energy intensive materials such as metals and fibreglass many-fold in mass basis.

The "no harvest" land-use reference system applied in this paper for all the scenarios studied may be considered unrealistic in large scale, but it is consistent with the conceptual basis to describe the life cycle impacts related to wood utilization as *it is assumed to occur*.[27] It should be noted that the fundamental purpose of ALCA is not to describe economic feasibility but the environmental impacts that can be attributed to the system studied. Our results illustrate the average life cycle impacts of each unit of wood harvested in the scenarios studied. Another option would be to study the difference between two alternative forest management scenarios, in accordance with the consequential LCA (CLCA).[26] In such a case both the reduction in forest C sink and the substitution credits would be lower in absolute terms compared to our analysis, thus the net carbon emissions per wood harvested would be the same order of magnitude in comparison to the results presented in this paper (see SI SI2). Additional aspects for further studies are the market rebound effects excluded in our analysis. Such effects may increase the overall carbon emissions related to wood utilization due to reduced avoided emissions through substitution[50] but also decrease the carbon emissions due to incentives to invest in increased forest growth.[51] Market-mediated effects are highly influenced by existing and anticipated policies and regulation, and subject to significant uncertainties in the long run.

3.7. Comparison to Previous Studies. The impacts on net carbon (equivalent) emissions of the overall wood utilization in other boreal regions have been studied for Canada in seven various scenarios up to 2050 by Smyth et al.[18] and for Sweden in three various scenarios up to 2105 by Lundmark et al.[19] Both of these studies drew more positive conclusions on the climate benefits of forest biomass utilization compared to our study, but also deviated in some key assumptions from our paper. Smyth et al.[18] took forest C sink impacts into account by comparing the studied seven scenarios to the "business as usual" reference scenario. They concluded that the net carbon equivalent emissions can be reduced the most if the utilization rate of clear-cut stem wood is increased and burning of forest residues in situ is stopped. Apart from that particular scenario, the highest emission reduction by Smyth et al.[18] was achieved in the scenario where harvest levels were reduced. This means that the other five scenarios studied by Smyth et al.[18] relying on increased harvest rates resulted in higher net carbon equivalent emissions compared to reduced harvest rates. Lundmark et al.[19] integrated the absolute forest C sink with the avoided emissions through substitution and, thus, totally excluded the impacts of wood harvesting on forest carbon sink. Therefore, their results are not comparable to our results. Overall, the differences between various studies may result from a number of factors, and an objective comparison of the results and conclusions would require a careful review or meta-analysis.

3.8. Concluding Remarks. It is exceptionally unlikely (cumulative $P \leq 1\%$) that the wood utilization in Finland provides significant unit reductions in net carbon emissions within the upcoming 100 years. This is because the benefits from avoided fossil emissions through material and energy substitution are lost mainly by the reduction in the forest carbon sink due to wood harvesting. The forest C sink reduction effect would be even more significant if shorter than 100-year time horizons were considered. This kind of trade-off creates a challenge to the global climate policy: while fossil C emissions are partly avoided by wood utilization, other emission reduction measures are needed to offset the reduced forest carbon sink generated by wood harvesting. This is problematic as all the emissions from fossil fuels need to be reduced within a few decades, and even negative net emissions will likely be required globally before 2100 in order to limit the global mean temperature increase below 2 °C.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b00122.

The calculations and assumptions with references (SI1), additional description of the methods and additional sensitivity analysis (SI2) (PDF)
(XLSX)

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Notes

The authors declare no competing financial interest.

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