Supporting Information (SI2) for

Climate change mitigation challenge for wood utilization – the case of Finland

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In this supporting information (SI2), additional description of the methods and additional sensitivity analysis are presented.

9 pages, 3 figures, 2 tables

Methods

Description of the data sources

To calculate material and energy inputs and outputs of wood utilization in Finland in 2010, we derived data from the official statistics of Finland. Domestic, imported and exported wood flows were derived from (1). Most of the primary energy consumed within the forest industry was based on bioliquids and solid biofuels derived from wood (1). We derived the data for all the other energy consumption of the forest industry including fossil fuels, peat, and purchased electricity and heat from LUKE (1) and Statistics Finland (2). As forest industry both purchases and sells electricity and heat from and to third parties, we considered the consumption of electricity and heat on net purchase basis (2).

To study material and energy inputs and outputs of wood utilization in Finland in the scenarios relying on 2050 wood utilization structures, we used the data from the national *Low Carbon Finland 2050* scenarios (3, 4, 5). The particular scenarios have been prepared for an energy and climate roadmap for Finland up to 2050 of a Parliamentary Committee on Energy and Climate Issues established by the Finnish government in 2013 (6). In addition to 2010 wood utilization structure, we considered five different structures entitled as ‘Base’, ‘Constant growth’, ‘Save’, ‘Stagnation’, and ‘Change’, which are based on different storylines on the development of the Finnish economy up to 2050. According to the scenarios, the GHG emissions in Finland (excluding the land use, land-use change and forestry sector) are estimated to be reduced by 30% until 2050 compared to the level of 1990 in ‘Base’, and by 67-85% in the four latter mentioned scenarios, respectively (3). The amount and type of wood used, wood products produced and the energy requirement of the wood processing vary significantly between the scenarios. The quantitative description of the wood flows in the scenarios is based on expert estimations and on the use of SF-GTM partial equilibrium model of the Finnish forest sector (7, 8). The development of the energy system in the scenarios is based on the model runs carried out by VTT-TIMES model, an application of ETSAP TIAM model (9, 10, 11). We took the domestic, imported and exported wood flows in the 2050 wood utilization structures directly from Kallio et al. (4). We took the use of fossil fuels, electricity and heat in the pulp and paper industry in the 2050 wood utilization structures directly from Lehtilä et al. (3). We assessed the use of fossil fuels, electricity and heat in the saw mill industry in the 2050 wood utilization structures [not presented separately by Lehtilä et al. (3)] by adjusting 2010 figures (2) with respect to the change in the overall production volume of saw mill industry until 2050 in accordance with Lehtilä et al. (3). The share of net electricity purchase was assumed to remain the same than in 2010. Electricity consumption in biorefineries was assumed in accordance with McKeough and Kurkela (12) for an integrated production concept which minimizes biomass input.

To convert material and energy balance of the wood utilization in Finland into life cycle carbon balance, we made several assumptions (see SI1 and Table 2 of the paper). These included conversion factors from mass or volume of biomass to energy content, reduction in the forest carbon sink due to wood harvesting, round wood requirement in pulping of imported pulp, CO_2 emission factors of fuel combustion, CO_2 emission factors of electricity and heat production, CO_2 emissions embodied in pulp and paper industry imports, carbon content of wood products, and substitution factors (avoided CO_2 emissions) for mechanical wood products, paper, paperboard and energy products. We handled each of these assumptions stochastically. First, we defined the mean value and 95% central confidence interval for each 30 input parameters (see SI1 and Table 2 of the paper for details). For most of the parameters, we set the mean value based on an appropriate literature value and the uncertainty range based on our own estimation. For some of the parameters, we defined the uncertainty range based on appropriate literature values and set the mean value in the middle of the range. Second, we assumed a symmetric triangular distribution for each of the parameters handled stochastically.

Based on the analysis shown in the paper (Fig. 1 and Table 2) and SI1, the parameter contributing the most to the extended life cycle carbon balance and its uncertainty was 'reduction in the forest C sink per the C content of wood harvested over 100 years (RC_{100})'. In the following section, we give an explanation of the mean value and uncertainty range applied for the particular parameter.

Reduction in the forest carbon sink due to wood harvesting

Wood harvesting influences forest carbon stocks, and this impact needs to be taken into account when assessing the net carbon emissions of wood utilization (13, 14). First, wood harvesting immediately reduces forest C stock with the amount of carbon harvested (15). Second, forest growth following harvest increases forest C stock, but in the boreal region the recovery of the C stock taking place before the harvest takes decades to be paid back (16). Third, cutting growing trees causes forgone C sequestration as long as forest would have continued to sequester carbon if the trees were not harvested (17, 18). The lowered forest C stock in wood harvesting scenario in comparison to reference scenario where the studied wood is not harvested can be considered as cumulative reduction in forest C sink, regardless of whether or not forests act as a net carbon sink in absolute terms (14, 15, 19, 20, 21).

We considered the impact of wood harvesting on forest C sink over 100 years assuming continuous and constant wood harvesting scenarios in comparison to a 'no harvest' scenario. Cumulative reduction in the forest C sink over a given time horizon per the C content of wood harvested over the same time horizon can be described using a dimensionless indicator presented and titled as 'relative carbon indicator' (RC_T) by Pingoud et al. (15). The RC_T shows how much of the harvested carbon would have remained in forest over the studied time horizon T if not harvested. In the following, we use the term RC_T to refer reduction in the forest C sink per the C content of wood harvested over the given time horizon. As we are not aware of any study in which the development of forest C stocks at landscape level without any further harvesting would have been assessed, we determine below the assumption used in this paper for the RC_{100}.

To illustrate the RC_{100} considering only the stem wood C stocks with and without final fellings, we assume the development of the stem biomass of a Scots Pine stand without thinnings (see 22). If such a stand is harvested at the age of 100 years at time t=0 and reforested with an identical wood population and C stock development, the stem wood C stock at time t=100 reaches the initial stem wood C stock. However, considering that the stem wood growing would have continued over the studied 100-year time horizon without final felling, the stem wood C stock would have increased from the initial level (Fig. S1). In such a case the RC_{100} is 0.33 (black dotted curve in Fig. S2). Harvesting such a stand every year results in RC_{100} of 0.66 (black bolded curve in Fig. S2). In addition to stem wood carbon stock, consideration of dead wood, litter and soil carbon stocks increases the value of RC_T. This is due to the fact that in the wood harvesting scenario the C stock in the deadwood pool is lower in comparison to the 'no harvest' scenario, residues generated and left at the site after final felling decays releasing carbon dioxide, and soil organic carbon stock reduces in the few years following final felling (18, 23).

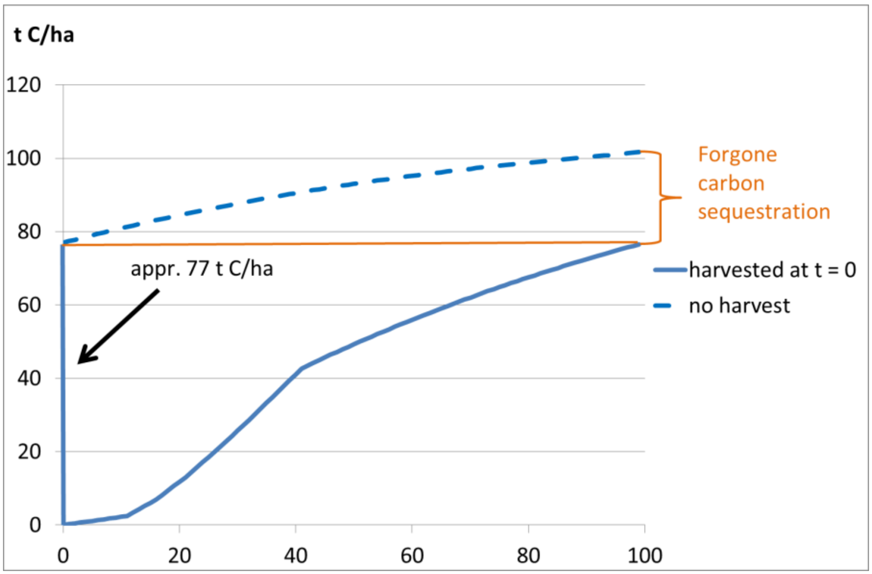

Figure S1. Development of the stem wood biomass of a Scots Pine (Pinus Sylvestris) stand with and without final felling at t=0 based on the growth curve presented in Pingoud et al. (22).Stand age 100 years at t=0.

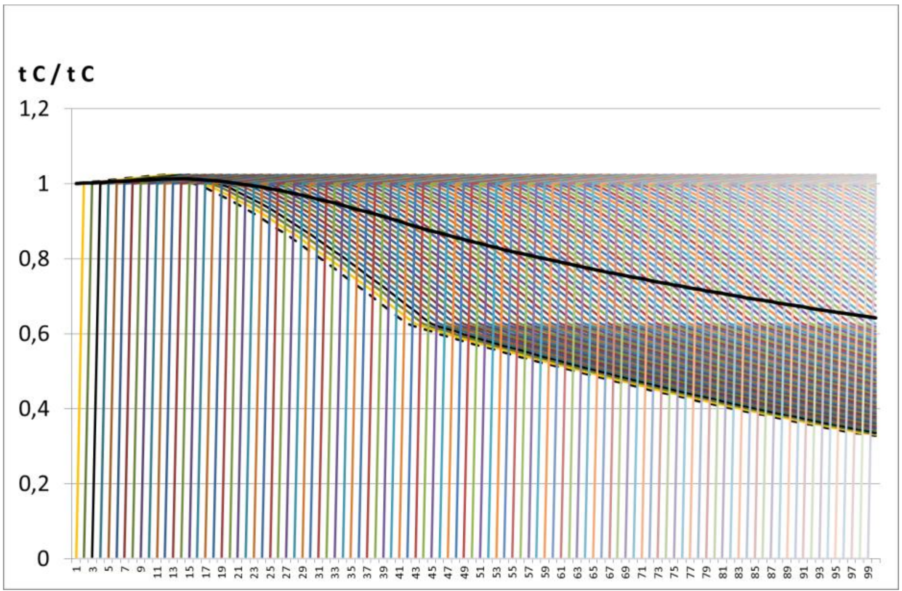

Figure S2. Cumulative reduction in the stem wood C sink per the C content of wood harvested (RC_T); one Scots Pine (Pinus Sylvestris) stand [based on the growth curve presented in Pingoud et al. (22)] harvested every year at 100-years age; The black dotted curve shows the RC_T for the stand harvested at first year, the black bolded curve shows the accumulated RC_T for all the stands harvested by the time T.

Forest management typically includes first and intermediate thinnings before final fellings (24). Thinnings typically improve the growth of the living trees left at the site, but the overall forest C stock remains lower than that of unthinned forest (23). In particular, additional thinnings in young forests in good growth conditions may result temporarily in significant forgone C sequestration (8, 17, 25). According to Helin et al. (25), in comparison to 'no harvest' scenario, wood harvesting in the first year consisting of first and intermediate thinnings and final fellings in a typical forest land-scape in Finland results in RC_{100} of roughly 0.6. It can be expected that continuous constant wood harvesting scenario would increase RC_{100} as shown for the case of stem wood C stocks in Fig. S2.

Hynynen et al. (26) assessed the impact of forest management in Finland on biomass supply and forest resource development in four different continuous national scenarios from 2010 to 2109. Based on the wood harvesting and forest C stock data presented by Hynynen et al. (26), RC_{100} varies between 0.7 and 1.3 for various combinations of the comparisons of the scenarios (Fig. S3). Kallio et al. (4, 5) presented the wood harvesting and forest C sink data for the so called Low Carbon Finland 2050 scenarios between 2010 and 2050. By comparing those scenarios to each other, the RC_{40} can be calculated to vary between 0.7 and 3.0 for various combinations of the comparisons of the scenarios. Sievänen et al. (17) presented more and less ambitious increase in energy wood harvesting added to industrial wood harvesting in Finland between 2007 and 2042. Pingoud et al. (15) showed that the RC_{35} was roughly 2 for the energy wood harvesting presented by Sievänen et al. (17). It should be noted that in the scenarios presented by Hynynen et al. (26), Kallio et al. (4, 5) and Sievänen et al. (17), the wood utilization were not constant over the studied time horizon. As the RC_T tends to be higher with shorter time horizons [Fig. S2, S3, Pingoud et al. (15), Helin et al. (25)], it can be expected that the RC_T based on Kallio et al. (4, 5) and Sievänen et al. (17) would be lower if 100-year time horizon would be applied like in this paper.

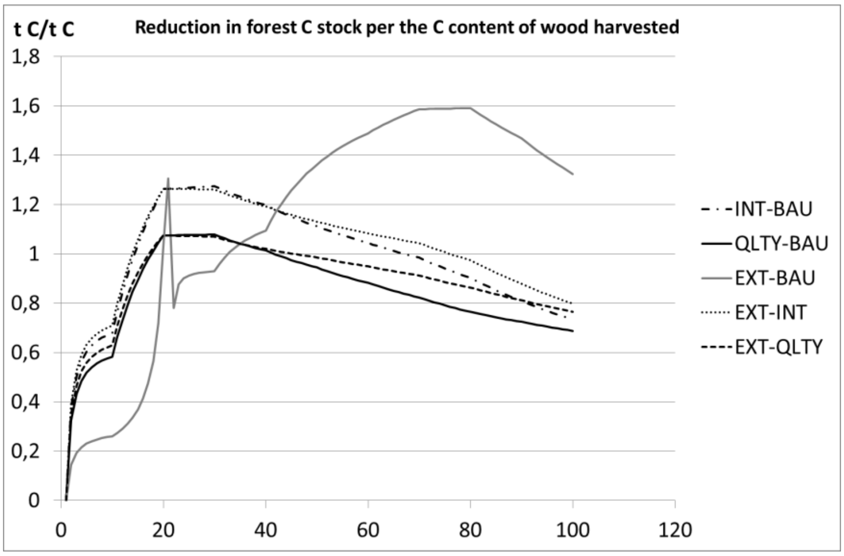

Figure S3. Cumulative reduction in the forest C sink per the C content of wood harvested as a difference between combination of comparison of various national forest management scenarios. 'BAU' refers to 'business as usual', 'INT' to 'active forest sector and intensive biomass production', 'QLTY' to 'high-quality raw material production for the forest industry and bioenergy', and 'EXT' to 'decreasing forest industry activities—increasing non-material services' scenario. The data for the scenarios derived from Hynynen et al. (26).

Helin et al. (25) assessed the C stock development for 'no harvest' scenario of a normal forest using forest growth data for a typical forest landscape in Finland. According to their analysis, the forest C stock increased three-fold in 100 years if not harvested. Assuming that the same C stock increase is applicable at national level in Finland if the forests were not harvested, forest management scenarios presented by Hynynen et al. (26) would result in RC_{100} varying from 1.0 to 1.2. However, unmanaged forests may pose higher risks for damages such as storms, fires and attacks by insects or diseases (27, 28). Thus, RC_{100} determined for any forest management scenario in comparison to 'no harvest' scenario may be lower than the range presented above. In this paper, we assumed that the upper limit (97.5%:ile value) for the RC_{100} is the average value of the range derived above (i.e. 1.1), the lower limit (2.5%:ile value) equaling 0.4, thus the mean value equaling 0.7.

Additional sensitivity analysis

We measured the sensitivity of the extended life cycle carbon balance calculated in the paper to the uncertainty of each of the input variables using Spearman's rank correlations (ρ). Spearman's rank correlation is a nonparametric measure of statistical dependence between two variables ($-1 \leq \rho \leq 1$), and it has the advantage over the common Pearson correlation that it does not require the dependence between the quantities to be linear but only monotonic. If the value of ρ is 1 or -1 for a specific variable, it means that the result value is fully determined by the uncertainty of the particular variable. Spearman's rank correlation (ρ) values between -1 and 0 means that the increase in the value of the variable decreases the value of the result. The opposite holds true for the ρ values between 0 and 1.

Clearly, the most important parameter contributing to the uncertainty of the extended life cycle carbon balance was 'reduction in the forest C sink per the C content of wood harvested over 100 years (RC_{100}) for each of the scenarios studied. This is indicated by the Spearman's rank correlation (ρ) values of 0.9 for the particular parameter (Table S1). The second most important parameter contributing to the uncertainty of the result was 'substitution factor for sawn wood and wood-based panels' for each of the scenarios studied (ρ values between -0.2 and -0.3). In the following we analyzed how small RC_{100} should be, or alternatively how large 'substitution factor for sawn wood and wood-based panels' should be in order to fulfill a given emission reduction requirement with a given probability. These additional analyses were carried out separately by determining either of these parameters deterministically while keeping the other parameters stochastic as presented in Table 2 of the paper. The emission reduction requirements studied were 0%, 50%, 80% and 100% (t C reduced per t C harvested), and the required likelihoods were 'likely' (cumulative P≥66%) and 'virtually certain' (cumulative P≥99%). Achieving emission reductions, especially at least 50% require much lower RC_{100} values than originally applied or much higher 'substitution factor for sawn wood and wood-based panels' (Table S2). This holds true for both the studied likelihood requirements, however, 'virtually certain' probability is more challenging than 'likely' probability requirement (Table S2).

Table S1. Spearman's rank correlation coefficients (ρ) for extended life cycle carbon balances for various scenarios studied.

Input variable	2010	Base	Const. growth	Save	Stagn.	Change
reduction in the forest C sink per the C content of wood harvested over 100 years (RC100)	0.88	0.89	0.89	0.89	0.90	0.91
substitution factor for sawn wood and wood-based panels (concrete, steel substitution)	-0.26	-0.24	-0.29	-0.28	-0.27	-0.23
substitution factor for energy and postused mechanical wood products (fossil fuel substitution)	-0.20	-0.18	-0.21	-0.22	-0.25	-0.24
substitution factor for paper products (fossil fuel substitution)	-0.18	-0.15	-0.12	-0.11	-0.08	-0.09
substitution factor for paperboard products (plastics, fossil fuel substitution)	-0.17	-0.19	-0.11	-0.13	-0.11	-0.10
C content of paper and paperboard products	-0.07	-0.06	-0.05	-0.05	-0.04	-0.04
CO_2 emissions from production of consumed heat (net purchase) in 2010 activities	0.06	n/a	n/a	n/a	n/a	n/a
average dry-fresh density of wood	0.05	0.06	0.05	0.06	0.06	0.06
CO_2 emissions from production of consumed electricity (net purchase) in 2010 activities	0.04	n/a	n/a	n/a	n/a	n/a
CO_2 emissions embodied in pulp and paper industry imports	0.04	0.03	0.00	0.01	0.00	-0.00
lover heating value (LHV) of solid wood fuels in small-scale housing	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02
lover heating value (LHV) of solid wood fuels in heating and power plants	-0.03	-0.02	-0.02	-0.02	-0.02	-0.02
CO_2 emissions from wood combustion	-0.03	-0.02	-0.02	-0.03	-0.03	-0.03
energy consumption of converting exported pulp to paper	0.02	0.03	0.03	0.03	0.02	0.02
C sequestration into harvested wood product (HWP) pool in 2010	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
CO_2 emissions from peat combustion	0.02	n/a	n/a	n/a	n/a	n/a
round wood requirement in chemical pulping	0.02	0.00	0.01	0.01	0.01	0.01
CO_2 emissions from heavy fuel oil combustion	-0.02	n/a	n/a	n/a	n/a	n/a
C content of sawn wood products and wood pulp	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
CO_2 emissions from coal combustion	0.01	n/a	n/a	n/a	n/a	n/a
the share of fossil fuel upstream CO_2 emissions from the combustion emissions	0.01	-0.00	-0.00	-0.01	-0.01	-0.01
CO_2 emissions from fuel consumption in wood harvesting	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
round wood requirement in mechanical pulping	0.01	0.01	0.01	0.01	0.01	0.01
lover heating value (LHV) of wood pellets	0.01	n/a	n/a	n/a	n/a	n/a
CO_2 emissions from natural gas combustion	0.00	n/a	n/a	n/a	n/a	n/a
CO_2 emissions from other fuel (REFs, liquefied petroleum gas and other biofuels) combustion	0.00	n/a	n/a	n/a	n/a	n/a
CO_2 emissions from production of consumed heat (net purchase) in 2050 structures	n/a	0.04	0.04	0.03	0.03	0.02
CO_2 emissions from production of consumed electricity (net purchase) in 2050 structures	n/a	0.07	0.07	0.06	0.06	0.06
CO_2 emissions from fossil fuel combustion in 2050 structures	n/a	0.07	0.06	0.04	0.04	0.04
the share of fossil fuels in total fuel consumption of forest industry in 2050 structures	n/a	0.03	0.03	0.02	0.02	0.01

Table S2. Values required for either of the two most important parameters, i.e. 'reduction in the forest C sink per the C content of wood harvested over 100 years (RC100)' or 'Substitution factor for sawn wood and wood-based panels' in order to reach the given emission reduction level (t C reduced per t C harvested). Both of the analyzed parameters determined deterministically and analyzed separately. The other parameters kept stochastic as presented in Table 2 of the paper. The ranges represent the minimum and maximum values depending on the scenarios studied. Values without parenthesis for the 'likely' probability (cumulative P≥66%) and values within the parenthesis for the 'virtually certain' probability (cumulative P≥99%).

Ranges required/applied for parameters analyzed deterministically	**0% emission reduction**	**50% emission reduction**	**80% emission reduction**	**100% emission reduction**	**Original 95%:ile range applied**
Substitution factor for sawn wood and wood-based panels in minimum	2.1…2.6 (3.7…4.5)	5.2…6.4 (6.8…8.3)	7.1…8.6 (8.8…10.6)	8.4…10.2 (10.0…12.3)	0.5…2.0
Maximum reduction in the forest carbon sink per the amount of wood harvested (RC_{100})	0.5…0.6 (0.3…0.4)	0.0…0.1 (-0.2…0.0)	-0.3…-0.2 (-0.4…-0.3)	-0.5…-0.4 (-0.6…-0.5)	0.4…1.1

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