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Research article

Effect of increased wood harvesting and utilization on required greenhouse gas displacement factors of wood-based products and fuels

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ABSTRACT

A displacement factor (*DF*) may be used to describe the efficiency of using wood-based products or fuels instead of fossil-based ones to reduce net greenhouse gas (GHG) emissions. However, the DFs of individual products and their production volumes could not be used alone to evaluate the climate impacts of forest utilization. For this reason, in this study we have developed a methodology to assess a required displacement factor (*RDF*) for all wood products and bioenergy manufactured and harvested in a certain country in order to achieve zero CO_2 equivalent emissions from increased forest utilization over time in comparison with a selected baseline harvesting scenario. Input data for calculations were produced with the simulation model, Monsu, capable of predicting the carbon stocks of forests and wood-based products. We tested the calculations in Finnish conditions in a 100-year time horizon and estimated the current average *DF* of manufactured wood-based products and fuels in Finland for the interpretation of *RDF* results. The results showed that if domestic wood harvesting will be increased by 17–33% compared to the basic scenario, the *RDF* will be 2.0 to 2.4 tC tC^{-1} for increased wood use in 2017–2116. However, the estimated average *DF* of manufactured wood-based products and fuels currently in Finland was less than 1.1 tC tC^{-1}. The results indicate strongly that the increased harvesting intensity from the current situation would represent a challenge for the Finnish forest-based bioeconomy from the viewpoint of climate change mitigation. For this reason, there is an immediate need to improve reliability and applicability of the *RDF* approach by repeating corresponding calculations in different circumstances and by improving estimations of *DF*s on country levels.

1. Introduction

According to the ambitious targets of climate change mitigation made in the Paris Agreement, there is a need for rapid and effective reductions in global greenhouse gas (GHG) emissions. The Paris Agreement aims at holding the increase in the global average temperature well below 2 °C, compared to pre-industrial levels, and pursues an even smaller increase of 1.5 °C (United Nations, 2015). Boreal forests and forestry may largely contribute to the global carbon cycle and mitigation of climate change. This is because boreal forests sequestrate large amounts of carbon dioxide from the atmosphere and provide forest biomass for the growing needs of the bioeconomy, which will reduce the use of fossil fuels.

One way to reduce the GHG emissions from the production and use of fossil-based products and fuels is to replace them with wood-based products and fuels (e.g. Winkel, 2017). Increased use of wood-based products and fuels can limit GHG emissions by the substitution effect and enhance the removal of CO_2 from the atmosphere by increasing the carbon stocks in wood-based products. The climate benefits of wood utilization are typically considered self-evident if sustainable forestry holds, i.e. when the harvested forest area remains as a forest and new trees will replace the harvested trees in the area. The wood utilization is, however, more complicated from the viewpoint of climate change mitigation if time aspects are taken into account. Firstly, wood harvesting reduces the carbon stocks of forests, compared to unharvested forests (e.g. Heinonen et al., 2017). Secondly, most of the carbon in new wood-based products and fuels will also be released back to the atmosphere rapidly, especially from biofuels and paper products (IPCC, 2006). This will lead to a situation in which GHG emissions measured as carbon dioxide (CO_2) equivalents are increased in the atmosphere in

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a certain time interval if harvested wood with substitution effects cannot compensate for carbon debt in forests before the new forest growth. From a climate change mitigation point of view, increased biogenetic CO_2 emissions is analogous to an increase in fossil-based carbon emissions, especially when studied over short time periods. In this sense, to gain climate benefits over time, harvested wood should be used for products and fuels that would release less GHG emissions to the atmosphere than substituted fossil-based products and fuels. Additionally, we should simultaneously increase carbon sequestration in forests.

In recent years, the climate impacts of forest-based bioeconomy have been assessed in many simulation-based studies, considering changes in carbon stocks in forests and wood-based products and fuels (Alam et al., 2017; Braun et al., 2016; Baul et al., 2017a, 2017b; Gustavsson et al., 2017; Knauf et al., 2015; Lundmark et al., 2014; Pukkala, 2016; Soimakallio et al., 2016; Rüter et al., 2016; Werner et al., 2010). In many previous studies, the climate benefit of substituting non-wood products and fuels with wood-based ones have been quantified through a displacement factor (*DF*), which expresses the amount of reduced GHG emissions per mass unit of wood use, when producing a functionally equivalent product or fuel (Sathre and O'Connor, 2010). In its calculation, the GHG emissions of all stages of the life cycles of products and fuels are taken into account, but *DF*s do not cover the impacts of wood harvesting on the carbon stocks of forests and wood-based products and fuels.

When the interpretation of the climate impacts of wood-based products and fuels is based only on the values of *DF*s, changes in carbon stocks in forests and wood-based products are not considered. However, they should be considered in the evaluation of net climate impacts for forest biomass use over time. The predicted results of carbon stock development in forests by simulation models depend especially on the quality of input data and on models' capability to describe relevant carbon flow processes in forests. For assessing *DF*s, life cycle assessments of both wood- and non-wood-based products and fuels include also uncertainties. Although this methodology has been standardized (ISO, 14040:2006) and there exist guidelines for the calculation rules of LCA (JRC, 2010; PAS, 2050:2011; EN, 15804:2012). For example, forest industry produces a wide range of wood product types and materials, the *DF*s of which are difficult to assess on regional and market levels because of data gaps in real substitution situations and the challenges related to the GHG assessments in product comparisons. In practice, the assessments employ different choices and assumptions in the methodology and input data, which may be site- and region-specific.

The reported *DF*s have in most cases been positive for wood-based products (Sathre and O'Connor, 2010; Smyth et al., 2014; Werner et al., 2015; Rüter et al., 2016; Geng et al., 2017; Leskinen et al., 2018). This means that they cause less GHG emissions compared to fossil-based alternatives. In general, the use of wood-based products and fuels may be assumed to have positive net climate impacts over time, if their emission reductions due to *DF*s are greater than the reduction in the carbon stocks in forests and wood-based products and fuels in a selected time period.

In this study, the aim was to develop a methodology to assess a required displacement factor (*RDF*) for all wood products and bioenergy manufactured and harvested in a certain country in order to achieve zero CO_2 equivalent emissions from increased forest utilization over time in comparison with a selected baseline harvesting scenario. We applied the methodology in the real case of Finland to assess the *RDF* at the country level. In order to interpret the *RDF* results, a magnitude of average *DF*s for all domestic wood-based products and fuels (including also wood residues) produced in the Finnish forest industry was assessed.

2. Materials and methods

2.1. Calculation of required displacement factors (RDF)

The displacement factors for wood-based products and fuels were determined according to the following equation (Sathre and O'Connor, 2010):

$$DF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \tag{1}$$

where $GHG_{non\text{-}wood}$ and GHG_{wood} are the *GHG* emissions resulting from the use of non-wood and the wood-based alternative, expressed in mass units of carbon (C). WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood utilized in wood-based and non-wood alternatives expressed in mass units of *C* contained in wood.

In this study, *WU* in Eq. (1) includes all wood material (including bark) that is harvested from forest sites (see IPCC, 2006). Furthermore, the calculation of GHG emissions is based on the use of GWP (global warming potential) factors for different GHG emissions in order to express results as CO_2 equivalents of the emissions. GHG emissions represent fossil-based emissions along the life cycles of products and fuels in the techno-sphere.

The average *DF* for all domestic wood-based products and fuels (including also wood residues) produced in the Finnish forest industry in a certain year can be calculated as follows:

$$DF_F = \frac{\sum_1^n (DF_j \cdot HW_j + \cdots + DF_n \cdot HW_n)}{\sum_1^n (HW_j + \cdots + HW_n)} \tag{2}$$

where DF_j is the displacement factor of a wood-based product or fuel *j* and HW_j is the used amount of roundwood for wood-based product or fuel *j*.

With the help of DF_F it is possible to calculate the total avoided GHG emissions per year due to the use of domestic wood for products and fuels by multiplying DF_F by the annual amount of harvested round wood in Finland (HW_F) (expressed in mass units of carbon). This substitution impact is an important part in the annual net carbon balance of forest utilization (*Net C*). *Net C* can be calculated as follows:

$$Net\ C = \Delta CF + \Delta CP + DF_F \cdot HW_F \tag{3}$$

where ΔCF *and* ΔCP are annual change in carbon stocks (mass units of carbon) of forests and wood-based products produced from domestic round wood in Finland, respectively. *CF* consists of the above- (CF_A) and below-ground carbon (CF_B) stocks, i.e., $CF = CF_A + CF_B$.

The term "$DF_F \cdot HW_F$" in Eq. (3) can be called the substitution impact of domestic *HW* that describes avoided GHG emissions caused by the domestic *HW* (cf. Eg. 2). The avoided emissions include fossil CO_2, nitrous oxide (N_2O), methane (CH_4) and fluorocarbons (*F*-gases) caused by human activities. According to the rules of the national GHG emissions inventory determined by the Kyoto Protocol, carbon in *HW* is considered as emissions decreasing the carbon stock in forests (Fig. 1). For this reason, the development of carbon stock in products should be monitored in the annual carbon balance calculations.

If ΔCF is positive in Eq. (3), forests act as carbon sinks. If *Net* C is negative, the forest utilization causes more CO_2 equivalent emissions than it reduces them.

The annual difference of *Net C* between basic (*Net* C_b) and increased (*Net* C_i) wood harvesting scenarios can be calculated as follows:

$$Net\ C_i - Net\ C_b = \Delta CF_i - \Delta CF_b + \Delta CP_i - \Delta CP_b + DF_{Fi} \cdot HW_{Fi} - DF_{Fb} \cdot HW_{Fb} \tag{4}$$

where CF_i and CF_b are forest carbon stocks (trees and soil), CP_i and CP_b are carbon stocks in wood-based products, DF_{Fi} and DF_{Fb} are average *DF*s for all domestic wood-based products and fuels, and HW_{Fi} and HW_{Fb} are the annual amounts of domestic round wood harvested and used for the products and fuels by national forest industries in the increased (*i*)

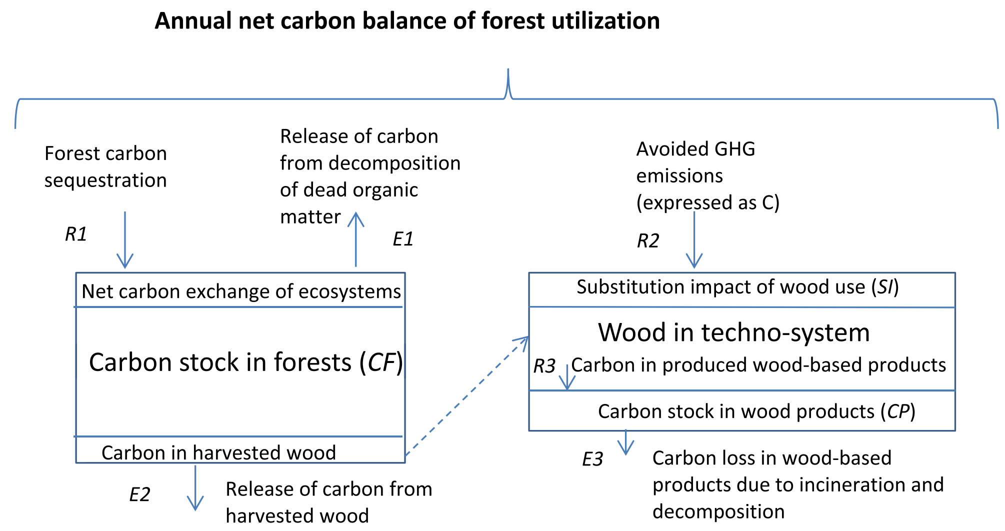

Fig. 1. Schematic description of carbon emissions (*E*) and removals (*R*) causing annual net carbon balance of forest utilization. $\Delta CF = R1\text{-}E1\text{-}E2$, $\Delta CP = R3\text{-}E3$ and $SI = R2$ when *E*s and *R*s are measured as positive values.

and basic (*b*) wood harvesting scenarios. DF_{Fi} and DF_{Fb} are equal if product- and fuel-specific displacement factors (DF_j) and the share of wood used for wood-based products or fuels *j* (HW_j) are the same in both scenarios (see Eq. (2)). In this case, $DF_{Fi} = DF_{Fb} = DF_F$.

If the result of Eq. (4) is negative, the increased wood harvesting scenario does not cause net climate benefits compared to the basic scenario. To obtain net climate benefits for a certain period, the climate substitution impact of increased wood harvesting should be higher than the estimated loss of carbon stocks in forests and wood-based products between the basic and increased wood harvesting scenarios.

Here we determine a minimum level for average *DF*s for all wood-based products and fuels manufactured from additional harvesting of domestic wood. Henceforth, it is referred to as the "required displacement factor" to achieve climate benefits compared to the basic harvesting scenario.

The required displacement factor (*RDF*) for time interval $[t_0,T]$ is calculated as follows:

$$RDF = \int_{t_0}^{T} (CF_b(t) - CF_i(t) + CP_b(t) - CP_i(t))/(HW_i(t) - HW_b(t))\ dt \tag{5}$$

where all amounts are expressed as tons of carbon. In this general equation, *HW*s are also time dependent as the amounts of *HW* can vary along time.

RDF in Eq. (5) describes the average *DF* of wood-based products and fuels manufactured from the additional *HW*s in the increased wood harvesting scenario during time interval $[t_0,T]$. The longer a period is, the more substitution effects from different stages of the life cycle of wood-based products and fuels will be included in *RDF*. For example, sawn wood can be considered to replace concrete and steel and the production of sawn wood will cause immediate substitution benefits. At the end of the original use of sawn wood, it can be used as fuel and replace fossil fuels. However, the energy substitution effects will occur clearly later (e.g. 35 years after the production). In addition, the cascading use will lengthen the duration of material use of products before their end use as fuel.

2.2. Simulation of input data for the determination of RDF

2.2.1. Outlines of the simulation software

In this study we produced changes in carbon stocks of forests and products for the *RDF* calculations using harvesting scenarios conducted using Monsu software (Pukkala, 2011), which has been used earlier in several scenario analyses on the impacts of forest management and harvesting intensity on forest growth, growing stock volume, timber supply and carbon balance of forestry (Heinonen et al., 2017, 2018a, b; Pukkala, 2011, 2014, 2016; Zubizarreta Gerendiain et al., 2016). In the simulations, the impact of gradual climate change on growth responses of different boreal tree species was considered by employing a new meta model approach (see Supplementary material 1). In all simulations, it was assumed the increase of annual mean temperature and precipitation in Finland would be by 2 °C and 6%, and the increase of atmospheric CO_2 concentration would rise to 430 ppm by 2100, under the RCP2.6 forcing scenario (multi-model mean climate projection, the Coupled Model Intercomparison Project 61 Phase 5 (CMIP5), see Ruosteenoja et al., 2016). As a result of this approach, the simulated growth responses of different tree species are similar.

The Monsu software calculates the carbon balances for the following carbon pools: (1) living forest biomass (Biom); (2) soil organic matter (Soil); and (3) wood-based products and fuels (Prod). The Soil and Prod pools are initialized with models (Pukkala, 2014) to estimate the initial amount of soil organic matter and the remaining mass of products manufactured before the start of the simulation period (see for details Heinonen et al., 2017). Litter production from tree biomass is calculated using tree species-specific turnover rates (Pukkala, 2014). The below-ground carbon stock includes dead organic matter from litter, harvest residues (including tree tops, roots, branches, needles/leaves and bark) and dead trees. Release of carbon through the decomposition of dead organic matter (CF_b) is simulated using the Yasso07 model (Liski et al., 2009; Tuomi et al., 2011a, 2011b). Carbon changes in wood-based products are calculated based on the carbon content of wood harvested during a time period, re-use of products prepared from *HW* and decomposition of newly prepared and old products.

Stems of harvested trees are first divided into saw log, pulpwood and energy wood assortments, and further into different wood product classes for the calculation of carbon balance (see Heinonen et al., 2017 for details). The amount of carbon in *HW* is calculated by multiplying the volumes of *HW* (m^3) by the carbon content factor (51,9% C) and tree species-specific average wood density (460 $kg\,m^{-3}$ Scots pine, 410 $kg\,m^{-3}$ Norway spruce, 580 $kg\,m^{-3}$ birch according to Repola, 2009).

2.2.2. Simulation of treatment schedules

We used a sub-sample of the sample plots of the 11th National Forest Inventory (NFI11, 2009–2013) of Finland (Korhonen, 2016), as the input forest data for the calculations of carbon pools of living forest biomass and soil organic matter. The forest data included one sample plot from every cluster. The used plots were located on forestland and assigned to timber production. The number of plots was 1890, 1393 and 1402 plots for southern, central and northern Finland, respectively (Heinonen et al., 2017, 2018a, b). We simulated different treatment schedules for every sample plot for ten 10-year periods (see Supplementary material 2). A sample plot was managed with a certain treatment if the predefined conditions for such treatment were fulfilled in the middle of a 10-year period. Country-level results were combined based on analyses done separately for these three regions. The most important input data in the Monsu simulations is presented in Supplementary material 3.

2.2.3. Harvesting scenarios and optimization

The basic scenario with 58 $Mm^3\,yr^{-1}$ cutting target for 2017–2116 was near the realized annual drain of saw log and pulpwood during 2004–2013 in different regions of Finland (i.e. 57.6 $Mm^3\,yr^{-1}$) for wood-based products and fuels (Finnish Forest Research Institute, 2014). The rest (left from 60 $Mm^3\,yr^{-1}$) was assumed to be small-sized household energy wood (Natural Resources Institute Finland, 2017). Regional cutting targets for saw logs and pulpwood were derived by summing the realized cutting volumes of 2004–2013 separately for the three regions. In the second scenario with the 67.2 $Mm^3\,yr^{-1}$ cutting target (INT1) for 2017–2116, the amounts for saw logs and pulpwood were 17% higher than in the 58 $Mm^3\,yr^{-1}$ scenario. In the third scenario (INT2), the amount for saw logs and pulpwood were 33% higher than in the 58 $Mm^3\,yr^{-1}$ scenario, i.e. 77 $Mm^3\,yr^{-1}$ were harvested annually during the ten 10-year periods (exactly: 76.7 Mm^3 for wood-based products and fuels, and the remaining 3.3 or 3.4 $Mm^3\,yr^{-1}$ were small-sized household energy wood). The INT2 scenario represents the planned harvesting intensity in 2025 (Ministry of Agriculture and Forestry in Finland, 2019). In all scenarios, the share of pulpwood was 60% of the *HW* in 2017–2116. Harvesting targets were not specified separately for different tree species.

In all scenarios, we applied the current forestry practices and the calculations started at the same situation in 2016. Furthermore, all scenarios had the same parametrization for the soil carbon model (Yasso07) and forest biomass growth happened according to the applied RCP2.6 forcing scenario. At the starting situation, the net increment of growing stock volume was 86 $Mm^3\,yr^{-1}$ in managed forest land.

The proportion of domestic wood utilization between saw log (40% of *HW)* and pulpwood (60% of *HW*) was the same over time in all scenarios. In addition, the area of managed forest land was the same in all scenarios, representing the current managed forest land used for timber production in Finland.

The objective of the treatment scheduling problem was to maximize timber production and profitability of forest management (net present value with a 3% discount rate), with even flow harvesting, targets for saw logs and pulpwood in each 10-year simulation period. The simulation and optimization methods used in this study have been described in detail in Heinonen et al. (2017, 2018a, b). As the Monsu results were reported at 10-year intervals, also the required average *RDF*s were calculated with a 10-year time step for 100 years based on differences in annual carbon stocks in forests and wood-based products and fuels between the basic scenario and two other harvesting scenarios.

2.3. Average displacement factor for all domestic wood-based products and fuels produced in the Finnish forest industry

Assuming that the share of the used amount of domestic wood for wood-based products or fuel *j* and their displacement factors (DF_j) are the same in the current situation (the basic scenario) and in the INTs scenarios, the required displacement factors (*RDF*) can be interpreted with the help of an average *DF* for all domestic wood-based products and fuels (including also wood residues) produced in the Finnish forest industry (DF_F, see Eq. (2)). If *RDF* is larger than DF_F, wood utilization causes more GHG emissions than it avoids. A DF_F value larger than *RDF* would result in climate benefits.

In previous studies, wood construction has been considered to be the best use from the view point of substitution effects at the current situation (Werner et al., 2015; Soimakallio et al., 2016; Rüter et al., 2016; Geng et al., 2017; Gustavsson et al., 2017). In Finland, the mechanical wood industry and plywood and veneer industries use about 43% of harvested industrial wood (Natural Resources Institute Finland, 2018). However, half of that wood is immediately combusted for energy (Natural Resources Institute Finland, 2017). The recent meta-analysis of *DF* studies produced by Leskinen et al. (2018) showed that the average *DF* of wood-based products in structural construction (e.g. building, internal and external wall, wood frame, beam) was 1.3 $tC\,tC^{-1}$. Furthermore, the average result for non-structural construction (e.g. window, door, ceiling and floor cover, cladding, civil engineering) was 1.6 $tC\,tC^{-1}$. On the basis of this information, it was assumed that the average *DF* of wood-based construction products per wood content in Finland is 1.45 $tC\,tC^{-1}$. Furthermore, it was assumed that the wood residues in production and construction stages will be utilized in wood combustion and they will replace fossil fuels with a *DF* of 0.8 $tC\,tC^{-1}$. By adding the substitution effects of wood-based products and the related wood residues, a *DF of 1*.13 $tC\,tC^{-1}$ was calculated (expressed per *HW*).

If wood combustion will replace fossil fuels, its *DF* can be considered to be about 0.8 $tC\,tC^{-1}$ (e.g. Soimakallio et al., 2016). In the future, the replacement will be smaller because energy sector emissions should rapidly decrease by 2050 due to climate change mitigation requirements. For example, clean electricity with heat pumps will increasingly replace traditional fossil-based heat and cooling production in the future (International Energy Agency, 2014). Thus, all combusted wood will not be used to replace fossil fuels in the future. For this reason, wood-based construction products with long time spans (over 30 years) can be assumed to have a lower end-of-life *DF* effect from combustion in the future. The end-of-life *DF* may be below 0.4 $tC\,tC^{-1}$ if less than half of fossil fuels will be replaced by wood-based fuels. Taking into account the end-of-life *DF* effect in the previous wood construction example with the *DF* of 1.13 $tC\,tC^{-1}$ we will get at most a *DF* of 1.33 $tC\,tC^{-1}$ (expressed per *HW*).

In 2016, about 58% of domestic round wood harvest (61.8 $Mm^3\,yr^{-1}$) was used in the pulp industry (Natural Resources Institute Finland, 2018) and about half of it was combusted for the industry's own energy supply (Natural Resources Institute Finland, 2017). No substitution benefits can be gained from this combusted biofuel because it is used for the manufacturing of pulp products. This adds the wood amount used for pulp products and the increased wood amount of wood-based product in the denominator of Eq. (1) (expressed per *HW*) will decrease the *DF* value of pulp products although the combusted biofuel is assumed to be carbon-neutral in the *DF* calculations of pulp products. Furthermore, pulp is mostly used for paper production in which the average *DF* per *HW* is most probably near zero (Achachlouei and Moberg, 2015). Cardboard can be assumed to mostly replace plastics with a *DF* of about 0.7 $tC\,tC^{-1}$ when the original estimation measured per wood contained in cardboard (Knauf et al., 2015) was changed per *HW*. The maximum benefits for pulp and paper would be achievable when they are used for energy in their end-of-life and they are credited for substituting fossil energy. In practice, Finnish pulp is used for paper and cardboard production (FAO, 2017). The amount of other pulp-based products is so small that it can be omitted from the estimation. In this case, the average *DF* of pulp products would likely be less than 1 $tC\,tC^{-1}$.

Considering the above-mentioned aspects of the Finnish forest industry's wood-based products and fuels, the current average DF_F is under 1.1 $tC\,tC^{-1}$.

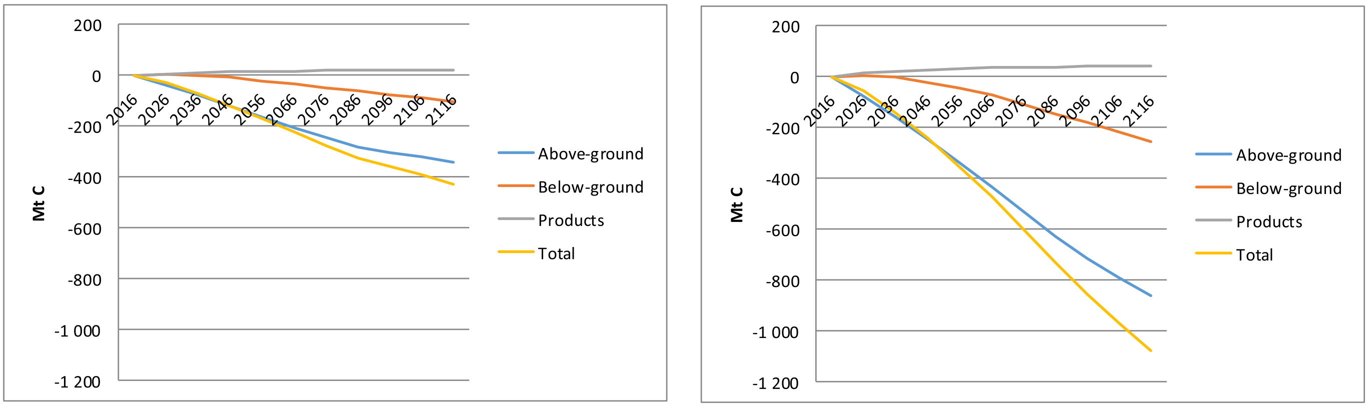

Fig. 2. Differences in carbon stocks (Mt C) in Finnish forests and wood-based products and fuels between the basic harvesting scenario and more intensive harvesting scenarios, INT1 (left) and INT2 (right). A positive value means that carbon stock of the increased harvesting scenario is higher than in the basic scenario. Timber cuttings in the scenarios: basic 58 $Mm^3 yr^{-1}$, INT1 67 $Mm^3 yr^{-1}$ and INT2 77 $Mm^3 yr^{-1}$ in 2017–2116.

3. Results

3.1. Differences in carbon stocks of forests and wood-based products and fuels

The intensive harvesting scenario INT1 leads to the situation in which the above- and below-ground carbons stocks of Finnish forests decrease, compared to carbon stocks in the basic scenario (Fig. 2). The decrease in above-ground carbon stock is more rapid than the decrease in below-ground carbon stock. The carbon debt from forests is much larger than from the increased carbon stock of wood-based products and fuels during the whole 100-year simulation period.

In the harvesting scenario INT2 in which cutting will increase by 33% compared to the basic scenario, the decrease of total carbon stock in forests and wood-based products and fuels will be 2.5 times higher for 100 years compared to the INT1 scenario, resulting in a clearly higher carbon debt.

3.2. Required displacement factors

The results between the basic wood harvesting scenario (58 $Mm^3 yr^{-1}$) and the increased wood harvesting scenario INT1 with 67 $Mm^3 yr^{-1}$ revealed that increasing the annual wood harvest by 9.6 $Mm^3 yr^{-1}$ resulted in *RDF*s of 2.0 tC tC^{-1} for wood-based products and fuels in 2017–2116 (Table 1). The carbon stock changes in the above-ground carbon stock of forests contributed the most to the required *RDF*s. The contribution of carbon stock in wood-based products and fuels was small but still evident. The increased wood harvesting scenario INT2 with 77 $Mm^3 yr^{-1}$ in 2017–2116 revealed that the *RDF* of the increased amount of wood-based products and fuels will increase over time (Table 1). *RDF*s obtained for 2017–2116 were 0.4 tC tC^{-1} larger than in INT1.

Fig. 3 illustrates the *RDF*s for the additional amount of round wood obtained from the INT1 and INT2 scenarios, as calculated separately for the 10-year periods. The results of INT1 show that the *RDF*s will peak in 2057–2066, 2067–2076 and 2077–2086 with2.2 tC tC^{-1}, and achieve the level of 1.8 tC tC^{-1} in 2107–2116. In the case of INT2, the peak value of *RDF* after the middle century (2077–2086) will be 3.1 tC tC^{-1}. *RDF* of INT2 will decrease to 2.6 tC tC^{-1} in 2107–2116. Compared to Table 1, Fig. 3 gives the same requirement for substitution impact, but instead of showing the average accumulated *RDF*, it illustrates the *RDF* of different 10-year periods.

In the INT1 and INT2 scenarios, all the *RDF*s for the additional harvestings are higher than the estimated current average *DF* of the Finnish forest industry's wood-based products and fuels (less than 1.1 tC tC^{-1}, see Section 2.3) except the *RDF* of the first 10-year time period (Table 1 and Fig. 3). Thus, during the next 100 years the increased harvesting of domestic wood will not cause climate benefits if the substitution effects of wood products and fuels correspond to the current situation and forest growth does not substantially increase from the level that was assumed in our model simulation.

The long-term *RDF* in the INT1 scenario is lower than in the INT2 scenario. However, even in the case of the INT1 scenario, the additional amount of wood-based products and fuels obtained from the increased harvests of 9.6 $Mm^3 yr^{-1}$ cannot lead to climate benefits by 2116 if the real average DF_F for wood-based products and fuels manufactured by the additional *HW* in 2017–2116 is not higher than 2.0 tC tC^{-1}. To achieve this level of *RDF* during the 100-year period is extremely difficult. The reason behind the difference between INT1 and INT2 is the carbon loss in forests per *HW* due to increased harvesting intensity in 2017–2116, compared to the basic wood harvesting scenario. This loss will increase more rapidly in INT2.

4. Discussion

4.1. Applicability of RDF approach and its implications on forest-based bioeconomy

The climate impacts have been typically reported in previous country-level simulation studies combined with changes in harvesting intensity and the substitution impacts of wood-based products and fuels (e.g. Braun et al., 2016; Gustavsson et al., 2017; Knauf et al., 2015;

Table 1

Required displacement factors (*RDF*) for additional amounts of wood-based products and fuels produced from domestic wood, compared to the basic harvesting scenario, for harvesting scenarios INT1 and INT2 for different time intervals starting from 2017. Timber cuttings in the scenarios: basic 58 $Mm^3 yr^{-1}$, INT1 67 $Mm^3 yr^{-1}$ and INT2 77 $Mm^3 yr^{-1}$ in 2017–2116.

Harvesting scenario	Required displacement factor *RDF* (tC/tC)									
	2017–2026	2017–2036	2017–2046	2017–2056	2017–2066	2017–2076	2017–2086	2017–2096	2017–2106	2017–2116
INT1	1.3	1.5	1.7	1.9	2.0	2.0	2.1	2.0	2.0	2.0
INT2	1.3	1.6	1.8	1.9	2.1	2.2	2.3	2.4	2.4	2.4

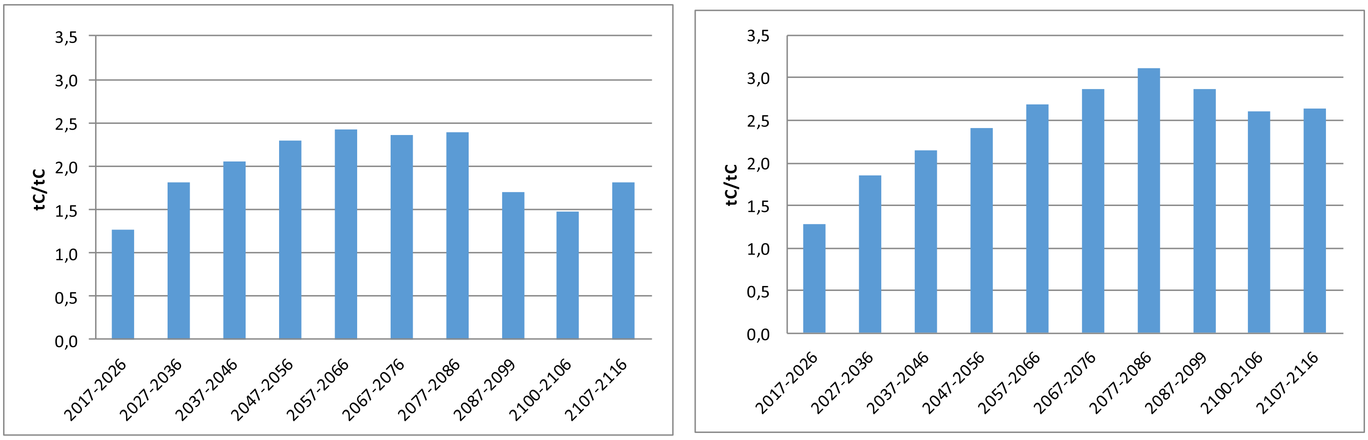

Fig. 3. Required displacement factors (*RDF*) of different 10-year periods for the additional amount of wood-based products and fuels produced from domestic wood in scenario INT1 (left) and scenario INT2 (right), compared to the basic harvesting scenario (58 Mm^3 yr^{-1}). Timber cuttings in the scenarios: INT1 67 Mm^3 yr^{-1} and INT2 77 Mm^3 yr^{-1}in 2017–2116.

Rüter et al., 2016). The results of such studies are, however, difficult to interpret from the viewpoint of the magnitude of *RDF*. This is because of missing information on changes in carbon stocks of forests and wood-based products. In this study, we calculated the *RDFs* for additional harvesting and utilization of domestic round wood for wood-based products and fuels in Finland in comparison to the selected basic harvesting scenario for the first time.

Some previous calculations are available in Finland on the development of forest carbon sinks in different wood utilization scenarios (e.g. Asikainen et al., 2012; Työ- ja elinkeinoministeriö, 2017), based on which the *RDF* values can be calculated. For example, in the context of the preparation of Finnish energy and climate strategy, three forest utilization scenarios (including all domestic round wood needed by the forest industry and energy sector) were developed: basic 79 Mm^3 yr^{-1}, policy 85 Mm^3 yr^{-1} and maximum 96 Mm^3 yr^{-1} (Työ- ja elinkeinoministeriö, 2017). Based on these, along with the increased harvesting intensity of domestic round wood from 79 to 85 Mm^3 yr^{-1} (calculations start from 2015), the *RDF* should be 0.4 Ct Ct^{-1} in 2015–2024, 0.8 Ct Ct^{-1} in 2015–2034 and 1.5 Ct Ct^{-1} in 2015–2044. If harvesting intensity increases from 79 to 96 Mm^3 yr^{-1}, the corresponding *RDFs* should be 1.5, 1.9 and 2.3 Ct Ct^{-1}, respectively. In these previous calculations based on the MELA model (MELA, 2012), the forest data corresponded to an earlier National Forest Inventory (10th) and the effect of gradual climate change on forest growth was not taken into account. In addition, the effects of changes in carbon stocks of wood-based products and fuels were ignored.

The method used in this work is very straightforward to apply at a country level outside Finland if suitable forest simulation models and sufficient input data is available. Required data includes the following inputs and models: national forest inventory sample plot data, model for simulating management scenarios for the plots, a forest products model (changes in carbon stocks in wood products), and a decomposition model for dead organic matter (Yasso07 can be used in many countries).

It is evident that differences in forest industries, forestry practices, forest growth and structure (age, tree species proportions) of forests between different countries will also cause variations in country-specific *RDFs*. In addition to the interpretation purpose of *RDFs*, there is a need to understand the magnitude of an average DF for all domestic wood-based products and fuels produced in a country. However, the *RDFs* for different countries can be used to clarify the relationships between countries' wood utilization and climate change mitigation needs over time. The results of this study implicate that climate benefits in Finland would be only obtainable in the planned future harvesting intensity if the carbon sequestration and stocks of forests could be increased considerably or if wood-based products with very high displacement factors and long time-spans could be developed and their share in the market rapidly increased.

Assuming that the average DF_F of the Finnish forest industry's wood-based products and fuels is 1.1 tC tC^{-1}, our results on RDF indicate that the additional harvesting (19.1 Mm^3 yr^{-1}) will cause cumulative emissions of 222 Mt C for the first 50 years and 491 Mt C for the whole 100-year period in comparison with the basic harvesting scenario. The values correspond to 815 Mt CO$_2$ equivalents for the first 50 years and 1801 Mt CO$_2$ equivalents for the whole period. In the case of INT1 (cuttings 67 Mm^3 yr^{-1}) the corresponding emissions will be clearly smaller, i.e. 367 Mt CO$_2$ equivalents for the first 50 years and 696 Mt CO$_2$ equivalents for the whole period. Finnish GHG emissions (excluding LULUCF) in 2015 were 55.6 Mt CO$_2$ equivalents (Statistics Finland, 2017).

4.2. Uncertainty of the results

Assumptions and uncertainties in models and their input data will contribute to the results of *RDF*. In addition, the uncertainty aspects related to the estimation of an average *DF* for all domestic wood-based products and fuels produced in a country play an important role in the interpretation of *RDF* results. In our study, the average *RDFs* during the 100-year period (about 2.0 and 2.4 tC tC^{-1}) obtained from the difference between the basic and INTs scenarios in 2017–2116 are clearly greater than our average displacement factors (1.1 tC tC^{-1}) for domestic wood-based products and fuels produced from Finnish forests (DF_F). Our estimation is quite similar to the average *DF* of 1.2 tC tC^{-1} obtained in the meta-analysis by Leskinen et al. (2018), in which *DFs* were derived from 51 case studies on products mostly covering wood used in construction materials. However, it is important to notice that substitution impacts of forest utilization on country levels have been estimated to be lower than estimations calculated for individual products. On the country level, two recent studies report average *DFs* of 0.5 tC tC^{-1} in Switzerland (DF_S) and Canada (DF_C) (Suter et al., 2017; Smyth et al., 2017). The results indicate that our rough estimation of DF_F may be overestimated and it can be considered as “a maximum value”. For this reason, our estimates of DF_F will probability lead to too positive interpretations for the climate impacts of wood utilization.

The Monsu model has been developed by utilizing large sets of empirical observations on forest growth and soil respiration (Yasso07 model), considering also changes in tree growth due to climate change. Sensitivity analyses have been conducted with the Monsu model on changes in the carbon pools of living forest biomass (above- and belowground), dead organic matter and wood products, as well as carbon releases from harvesting in regard to management and wood use intensity (Pukkala, 2014, 2018; Zubizarreta-Gerendiain et al., 2016). It can be assumed that Monsu can describe well the current carbon balance of forest utilization in Finland, but possible changes in environmental circumstances will be challenging for future predictions in all models. For example, simulation models (such as the Monsu model) seldom consider the effects of forest management and harvesting intensity, and climate change, on different abiotic and biotic disturbances (see e.g. Seidl et al., 2017; Reyer et al., 2017). The aging of forests and increasing volume of growing stock, especially in Norway spruce, may increase different abiotic and biotic damage to forests by windstorms, drought, insects, pathogens, and forest fires. As a result of large-scale disturbances, forest carbon stocks may decrease and large amounts of carbon may be released into the atmosphere (e.g. Kurz et al., 2008; Seidl et al., 2017; Reyer et al., 2017).

One way to check the reliability of our calculations is to compare them to corresponding results produced by different forest simulation models. As showed in Section 4.1, the MELA model will produce quite similar results, but the timeframe of the comparison was only 30 years. However, the comprehensive comparisons had not been available. For these reasons, it is important to carry out comparative studies in order to understand the behavior of forest simulation models and their possible limitations to improve conclusions about the reliability of the calculated *RDF*s.

5. Conclusions

In the method developed in this study, determination of the required displacement factor (*RDF*) for additional domestic wood harvesting was based on the difference in the carbon stocks in forests and wood-based products and fuels between two wood harvesting scenarios during a certain time period. A *RDF* expresses here the minimum efficiency of using forest biomass to reduce net GHG emissions.

The 100-year simulation of the use of domestic round wood by the Finnish forest industry revealed that increasing wood harvesting permanently by 19 $Mm^3\,yr^{-1}$ from the basic level (58 $Mm^3\,yr^{-1}$) would lead to a required displacement factor of 2.4 tC tC^{-1} for wood-based products and fuels obtained from the increased harvest in 2017–2116. This would compensate for the decreased carbon sinks in forests and changes in the carbon stocks of wood-based products. However, reported displacement factors for wood-based products and fuels and the share of wood-based products and fuels manufactured in Finland indicate that the average displacement factor of wood-based products and fuels produced in the Finnish forest industry (DF_F) is probably under 1.1 tC tC^{-1}. The lower value of DF_F compared to the assessed value of *RDF* means more net GHG emissions to the atmosphere.

The increase of 9.6 $Mm^3\,yr^{-1}$ in wood harvesting in Finland will cause only slightly smaller *RDF*s during the next 100 years compared to the increase of 19 $Mm^3\,yr^{-1}$. The results indicate that the increase of harvesting intensity in the current situation represents a challenge for the Finnish forest-based bioeconomy from the viewpoint of climate change mitigation. Our method is also applicable in other countries and it is straightforward to apply at a country level to calculate the *RDF*s for additional harvesting and utilization of domestic round wood for different wood-based products and fuels, if forest simulation models and required input datasets are available. However, to reduce the uncertainty of *RDF* calculations and to improve the interpretation of results, there is a need to produce corresponding results using also other simulation models and different circumstances. Better estimations on the average *DF* of wood-based products and fuels manufactured from domestic wood for the current situation and in the future are also needed.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.06.031.

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