Substitution and carbon storage impacts of harvested wood products - Effects of increased cascading with different market responses

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ABSTRACT

Background

The climate impacts of wood-based products can be measured by substitution impacts and changes in product carbon stocks. Cascade use of wood aims to increase resource efficiency and minimize the impact on the environment and climate, but it may lead to changes in the product portfolios of industries. Thus, measuring the overall impact is challenging. This study analyses the impact of wood cascading on the climate under varying market responses. Cascade use here refers to discarded sawnwood product utilisation in panel and wood-based composite production. The study utilises explorative scenarios where Finnish wood-based flows are modelled in an Excel-based material flow model, and discarded sawnwood flows are shifted from energy use to material use in the end-of-life stage. The Reference case represents the situation where discarded wood-based products are only used for energy. The scenarios portray plausible market responses to cascading, with cascade production either leading to additional wood-based panel and composite production, or substituting primary sawnwood products thus leading to lower overall harvest levels.

Results

The results show that the cascading can result in 1.6%-5.4% more avoided C emissions compared to reference when considering the substitution impacts, the carbon stock changes in wood products, and the avoided carbon loss from roundwood harvest. Besides the market response, the results vary depending on the time-period selected for the estimation of the average annual carbon stock change of wood products and the emission profile of non-wood products.
Conclusions

The results of this study indicate that cascading can contribute to climate change mitigation regardless of the market response, but it depends on the market response whether the reduction potential origins from wood-based products or indirect changes in the harvest levels. There are less avoided C emission gains in the technosystem, if cascading production substitutes primary production and therefore reduces the wood harvest. However, the opposite holds, if the average substitution impacts are significantly reduced in the future due to decarbonization of non-wood sectors. Thus, in the long-term, extending the carbon residence in the technosystem or in the ecosystem may provide a larger climate change mitigation potential than increasing the substitution impacts.

Keywords: carbon stock change, cascading, forest industries, greenhouse gas emissions, harvested wood products, substitution, substitution impact
Forests can contribute significantly to climate change mitigation by sequestrating carbon dioxide (CO\textsubscript{2}) from the atmosphere and storing it in live forest biomass and in soil. Harvested wood-based products with a long life cycle also store carbon outside forests, and the use of forest biomass can produce climate benefits when substituting fossil fuel intensive materials and fossil energy [1,2]. However, growing demand for raw materials for existing and new products (e.g. green chemicals or textile fibres) and for renewable energy for an expanding bioeconomy has been expected to increase the harvesting of forest biomass. Increased harvest levels may increase substitution benefits, but the reduced carbon sinks of forests may not be offset within a timeframe of decades unless the current end uses of wood products are radically altered [3,4]. Moreover, the climate benefits of wood use can be improved by more resource-efficient use of biomass [5].

According to the waste hierarchy and forest policy in the EU [6–8], use of a wood product should have a prioritised order: wood-based products, extending their service life, re-use, recycling, bio-energy and disposal. This is referred as wood cascading. Besides extending the lifetime of wood-based products in the technosystem, cascade use may also refer to more efficient utilisation of wood residues (e.g. bark and sawdust). Cascade use supports the goal of resource efficiency, using forest resources in a way that minimises impact on the environment and climate, and prioritising wood-based products that have higher economic added value and contribute to reducing emissions. In a single stage cascade, woody biomass is processed into a wood-based product and this product is used once more e.g. for energy. In a multi-stage cascade, woody biomass is processed into a wood-based product and this product is used at least once more in material form before disposal or energy recovery [9].
In the EU, industrial wood residues present a greater volume potential for cascade use, compared to waste wood [10]. However, discarded products can also offer an additional source for material cascading and create additional climate, social and economic benefits [11]. Generally, the cascade use of wood has been recognised as a strategy that contributes to an efficient development of the bioeconomy and to mitigating climate change [12]. However, many challenges in the calculations of cascading benefits for wood-based products, and the trade-offs between cascading and substitution benefits of energy use of wood, have recently been recognised [12,13]. Previously, greater importance was placed on substituting energy than increasing the cascade use of wood [14]. The potential of the optimised cascade use of wood can also be less favourable in terms of GHG emissions reduction in the energy sector, especially on meeting renewable energy targets in the EU [12]. Earlier studies suggested that the material cascading impacts of wood on GHG environmental sustainability can be relatively small, in relation to low cascading volumes [13,15,16]. Recently, Budzinski et al. (2020) [17] estimated that an increased cascade use of wood products may reduce the current total GHG emissions in Germany by 0.19%, and lifetime extension of wood-based products by 0.04%. However, if the cascading has indirect land-use impacts through avoiding the harvest of primary wood [18], it may offer greater carbon emission reduction [13,15,16] compared to non-cascading.

Finland has an emission reduction strategy to reach climate neutrality by 2035, and most of the emission reductions rely on energy sector decarbonisation [37]. It is estimated that the forest industries produce around 3 million tons of CO2 equiv. fossil GHG emissions annually to date, and with clean and renewable energy solutions it would be possible to reduce those emissions to 0.3 t of CO2 equiv. [37]. If the avoided biogenic carbon emissions were accounted for in addition to substitution, material cascade use could help to reach the carbon neutrali-
ty goal in the sector, although the impacts would be modest compared to the reductions possible in the energy sector.

The cascading potential in terms of avoided carbon emissions can be measured by the increased carbon storage effect and substitution impact of wood-based products. Substitution impact refers to the fossil-based GHG emissions avoided when a wood product substitutes for a non-wood product in a specific end use. Although the substitution impacts of wood-based products are widely recognised [e.g. 19–22] the phenomenon is still relatively poorly understood in relation to the extended service life of wood-based products [23] and cascade use of wood [12]. Producing longer-lifetime products does not necessarily lead to higher substitution impacts and vice versa, which means that their combined impacts need to be studied case by case. The joint analysis of cascade use of wood and substitution impacts over time is challenging due to the continual evolution of markets [24], and changes in the cascading use and reuse of non-wood products. The economy-wide environmental effects of increased cascade are still largely lacking [25]. One research gap relates to the impact of increased cascading use of wood, which may not only extend the carbon residence in wood-based products, but also implies changes in the product portfolios of industries and thereby the average substitution impacts of wood use.

As stated in earlier studies, end-of-life (discarded) wood cascading can have potentially greater environmental benefits when the cascading material substitutes for virgin resources [13,15]. However, direct virgin raw material replacement may be unrealistic in countries where typical cascading products (e.g. particle- and fibre board, medium-density particle board) are already based on secondary raw materials such as industrial residues. Finland, for instance, has a relatively small production volume of particleboard and the production is fully based on wood chips and sawdust originating from the wood industry. In the future, wood-
and wood-based composites are expected to increase their market shares [26]. Even if cascading does not directly replace virgin raw materials, it can offer additional market-level substitution impacts without increasing the harvest level. The third theoretical possibility is that cascaded wood products would start to substitute for traditional wood products, e.g. through the increased use of modern wood construction products. The substitution and carbon-storing benefits of cascading could be more limited here, depending on the product-level lifetimes and substitution impacts of the cascading product and the traditional wood product replaced. However, the indirect impact of avoiding harvest of virgin wood could occur if the market change decreases overall production volumes. It is considered likely that engineered wood products, possible also for cascading practices, will increase in demand whereas traditional sawnwood products may decrease [36].

This study sets out to analyse the climate impact of increased cascading use of wood-based products in Finland, in the light of various market responses to increased cascading. The climate impacts are studied as carbon emissions avoided through changes in the carbon stock of wood-based products and their substitution impact, and as avoided carbon loss from roundwood harvest due to increased cascading of wood-based products, compared to current wood-based production- and end-use market structure. This study analyses four ‘what if’ scenarios for increased cascading. Cascading use of wood-based products refers here to the recycling of discarded sawnwood products back to material use (panels, composites).

2 METHODS

2.1 Approach

This study utilised an explorative scenario approach, where the carbon emission reduction potential of material flow changes (in carbon tons) due to cascade use of wood is assessed. The cascading scenarios were based on plausible what-if situations in which discarded sawn-
wood products are utilised as a raw material for panels and wood-based composites instead of energy generation. To analyse the impacts of material cascading, a case study approach was adopted and the scenarios were established by altering the current Finnish wood flows with a wood flow model. The wood flow model was similar to material flow analysis methods [27], and carbon stock change, substitution calculation, and harvested roundwood volume changes were based on material volume changes in the technosystem via product portfolio. The study methodology constituted four phases: I) Reference scenario model and cascading scenario setup, II) scenario modelling, III) substitution, carbon stock change, and harvested roundwood volume assessment, and IV) assessment of the overall avoided carbon emissions in the cascading scenarios compared to the Reference.

The avoided carbon emissions were first calculated separately using substitution and carbon stock change of harvested wood-based products. Then, these measures were summed up to assess the overall avoided carbon emissions in the technosystem compared to the reference. As the avoided carbon emissions in the technosystem depend on the total harvested wood-based product volumes, they cannot be directly translated into ‘positive carbon emissions’ if one scenario performs better. Therefore, by additionally including avoided carbon loss from reduced roundwood harvesting, the overall avoided carbon emissions, including both forest and technosystem effects, can be compared to the reference.

2.1 Wood flow allocation model

The scenarios were built in an Excel-based wood flow allocation model, which is based on secondary sources presented in Kunttu et al (2020) [28]. The model quantifies the wood material flows in tons of C starting from forest harvesting, followed by the primary industry production (sawmilling, pulpmilling, energy, mechanical pulping, etc.), followed by side stream-
based production, and finally counting the total production in each product group and their allocation to different end-uses. Supplementary material A presents the end-uses and additional assumptions used for the model such as the production efficiencies and side stream formation and allocation.

### 2.2 Cascading assumptions and scenario development

The reference scenario represents the Finnish wood-based production- and end-use market structure in 2016. The harvest level was assumed to be 16 million tons of carbon, based on forest statistics [29]. In the reference scenario, material cascading is not introduced, and instead the discarded sawnwood products are utilised for energy as in the single-stage cascading definition.

The cascading scenarios in this study present material cascading of discarded sawnwood products. Only discarded sawnwood products are accounted for in cascading activities as they typically include less impurities such as glues, paints, or potentially hazardous substances that could limit the possibilities to cascade. Re-use is not a part of the analysis, and cascading options include only recycling and energy combustion. Discarded panels are used for energy due to the assumption that they contain impurities and therefore are not suitable for material cascading. Also, materials that have already been subject to cascading are not cascaded again but used for energy. The cascading scenarios thus follow the definition of multi-stage cascading.

In the scenarios it was assumed that only 50% of the sawnwood products from each production year will return to the material cascading loop (Table 1). This is based on IPCC (2006) [30] guidelines on the average half-lives for specific product groups, where the assumption is that half of the mass decays in a certain amount of time. As sawnwood products typically end
up in long-lifetime uses, it is safer to assume a high reduction of volume during the lifetime. In Europe, for example, the half-life for sawnwood products is generally 35 years [31]. The end-of-life stage assumptions are the same for the reference and cascading scenarios, with the difference being that in the cascading scenarios discarded sawnwood products are used as raw material for panel production (80%) and wood-based composites (15%), and only 5% is used for energy (Table 1), whereas in the reference all the discarded wood products are utilised for energy.

Some additional assumptions were made for the ‘from raw material to end-product’ gains regarding cascading. The original production efficiencies based on roundwood processing do not conform directly with cascading production because, e.g., debarking is not needed. Instead, we assume a material input–output ratio of 50% for cascaded products. The total material cascading potential in the scenarios varies from around 0.7 Mt C to 0.5 Mt C, and the same amount is directed away from energetic use in the cascading loop 1 in the Reference case (see Table 1).

**Table 1.** Material cascading assumptions in the cascading scenarios

| Cascading assumptions | Share of the initial production | End use and share |
|-----------------------|----------------------------------|-------------------|
| **Cascading loop 1**  |                                  |                   |
| Sawnwood              | 50% of total production          | 80% panels        |
|                       |                                  | 15% composites    |
|                       |                                  | 5% combustion for energy |
| Panels (from initial material flow, not recycled) | 50% of total production | 100% combustion for energy |
| **Cascading loop 2**  |                                  |                   |
| Sawnwood-based composites and panels | 100% of cascaded production | 100% combustion for energy |
The analysis was conducted for a total of four cascading scenarios. The market responses to cascading were studied through two types of scenarios: one scenario in which cascading increases the overall wood product production volume through additional production of panels and composites (CASPlus), and three scenarios in which the additional cascade production substitutes for primary sawnwood products at the market level and thereby reduces the production volume of primary sawnwood by 5% (CASred05), 10% (CASred10) or 20% (CASred20) in Finland. In the latter scenarios (CASred-), the harvest levels also decrease by an equivalent amount, since fewer sawlogs are required. There is an indirect consequence in the CASred -scenarios: the volume of side streams from sawmilling also decreases, which has a further decreasing impact on side stream-utilising production groups as well. The production volumes and their changes between the reference and cascading scenarios are presented in Figure 1 and in Supplement A.

It should be noted that, in the CASred scenarios, the cascading potential decreases at the same rate as the decreasing sawnwood product volumes. Additionally, all scenarios are calculated with two sets of displacement factor (DF) values, one with the current substitution impact estimates, and one considering a possible decarbonisation of the competing industries, leading to significantly lower average DFs (see section 2.3).
2.3 Substitution impact calculation

Product level substitution is typically measured by a displacement factor (DF) (eq 1) [e.g. 31]. The DF for specific product $i$ is calculated as

$$DF_i = \frac{GHG_{\text{alternative}} - GHG_{\text{wood}}}{WU_{\text{wood}} - WU_{\text{alternative}}} \quad (\text{eq 1})$$

where $GHG_{\text{alternative}}$ and $GHG_{\text{wood}}$ are the fossil GHG emissions resulting from the production of the non-wood and the wood alternatives expressed in mass units of carbon (C) derived from CO$_2$ equivalents over a timeframe of 100 years, and $WU_{\text{wood}}$ and $WU_{\text{alternative}}$ are the amounts of wood used in the wood and non-wood alternatives, expressed in mass units of C contained in the wood product. Using the standardised C units results in a unitless ratio (tC/tC), which makes the $DF$s comparable across widely varying cases and functional units. A
positive value for DF stands for reduced emissions, if an alternative product is replaced by a wood-based product, while a negative value stands for an increase in emissions.

The product-specific DFs used here were originally presented in the article by Hurmekoski et al. (2020) [33] and in the further expanded analysis about future changes in the article by Kunttu et al. (2020) [28]. In the absence of data for the emission factors of cascaded (recycled) wood products, we made a simplifying assumption that the product-level DFs are equal for the composite and panel products and energy recovery based on side-streams from virgin wood and on cascaded wood.

The substitution impacts include significant uncertainty regarding, for example, which wood-based product is assumed to replace which non-wood products, in which end use, where and when. Due to the absence of data for more elaborate analysis, a number of simplifying assumptions were required.

As a form of sensitivity analysis, the results were calculated with two different sets of DF values, one based on the current average DF and another based on a projected average DF for 2050 (see Supplementary B). The future DFs are based on the analysis of Kunttu et al. 2020 [28], assuming that there would be less emissions to be replaced in the non-wood sectors towards 2050 as a result of complying with the Paris agreement targets. This leads to reduced substitution impacts on average, as the currently more energy-intensive processes can reduce their emissions more relative to wood-based products.

*The production structure weighted avg DF* represents the average substitution impact that one unit of Finnish wood-based production results in under a certain production structure (see eq. 2 and eq. 3). The cascading volumes are excluded from the initial volume, because the cas-
cading substitution results in extra benefits without additional harvesting, i.e., the wood contained in the initial product is assumed to substitute for a non-wood product twice on the market level.

The DF for a wood-based product group (e.g. sawnwood-based products), $DF_{product\ group}$, is given as:

$$DF_{product\ group} = \sum_{i=1}^{n} End\_use_i \times DF_i \quad (eq.\ 2)$$

where end-use is the % share of intermediate product allocated to specific final wood product and end-use, and $DF_i$ is the (sub)product level displacement factor (e.g. for sawnwood-based furniture).

The production structure weighted avg DF, $\overline{DF_{HWP}}$, is given as:

$$\overline{DF_{HWP}} = \frac{\sum_{i=1}^{n} DF_{product\ group\ pg}}{initial\_volume} \quad (eq.\ 3)$$

where $DF_{HWP}$ is the production structure (volumes of harvested wood products) weighted average DF, $v$ represents the volume in the wood product group pg, and initial_volume is the total volume of produced wood products based on initial wood flow.

Finally, the total substitution, $DF_{tot}$ is calculated by multiplying the total volume of produced wood products (i.e., initial volume) with the production structure-weighted avg DF (eq4).

$$DF_{tot} = \overline{DF_{HWP}} \times initial\_volume \quad (eq.\ 4)$$
2.4 Harvested wood product carbon stock effect and carbon residence

In this study, the impact of material cascading on biogenic carbon emissions was based on the effect of expanded lifetimes of C contained in harvested wood products. This means that the C stock (eq 4) increases more rapidly over the years when more long-lifetime products are applied to the product mix. However, when the stock calculation is started from zero and the production volumes and structures remain the same, C inflow and C outflow eventually balance, regardless of whether material cascading is introduced or not. Thus, the speed of additional carbon stocking due to material cascade use in the technosystem also decreases over time, although it results in more C stored in the technosystem compared to when wood-product half-lives are shorter in the absence of material cascading. We excluded other market- and harvest-level changes from the analysis of C stock change.

Carbon stock in harvested wood products ($C_{i+1}$) was calculated based on the tier-2 equation presented by the IPCC (2006) [30]:

$$C_{i+1} = e^{-k}C_i + \left(\frac{1-e^{-k}}{k}\right) Inflow_i \quad (Eq. 4)$$

where $i$ is year, $C_i$ carbon content (total stock) in the specific product group, $k$ the decay constant for each product group category ($k = \ln(2)/\text{half-life}$ (see Table 2)), and $Inflow_i$ is the total carbon inflow to the specific product group annually.

Carbon stock change ($\Delta C_i$) is calculated as [30]:
\[ \Delta C_i = C_{i+1} - C_i \] (Eq. 5)

where \( \Delta C_i \) is the total carbon stock change in year \( i \). The annual net C stocking forms a parabolic curve, as the stock calculation is set to start from zero, meaning that historical C stocks are disregarded in the analysis. This is because they would not have had an impact on relative differences between the scenarios and Reference, which allowed us to isolate the material cascading impacts, *ceteris paribus*. The C stock development in these theoretical scenarios follow an exponential trend until they reach the saturation point. In that setting, the differences increase between scenarios and Reference (no cascading) towards saturation point. Therefore, we standardised the C stock changes to be more informative by using an average from the estimation period (years 1-10, 1-30, 1-50, and 1-100).

The half-life assumptions for product groups are based on IPCC (2006) [30], with the exception of composites, which is assumed to have the same half-life as panels (Table 2). The main difference between cascading scenarios and Reference is that there is an extra product group in inflows for sawmilling products that will continue to material cascading practices at the end-of-life stage (as panels and composites). This flow, which eventually enters cascading practices, is excluded from the original sawmilling inflow. Its half-life is assumed to be twice as long as virgin sawnwood (70 years).

**Table 2.** Half-life assumptions based on IPCC (2006) [30]

| Wood product group                      | Half-life (years) |
|-----------------------------------------|-------------------|
| Sawnwood (the share that is not utilised for cascading) | 35                |
| Wood-based panels                       | 35                |
| Mechanical pulp                         | 2                 |
| Semi-chemical pulp                      | 2                 |
| Kraft- and dissolving pulp              | 2                 |
Primary energy (CHP, Mill) 1
Liquid fuels 1
Cascaded sawnwood-based products* 70

*Includes the half-life of virgin sawnwood

Carbon residence (C_{res}) (Eq. 6) is another indicator for the carbon stock effect of harvested wood products. It quantifies the duration that carbon remains in the technosystem on average, calculated as:

\[ C_{res} = \frac{C_{i+1}}{Outflow_i} \quad \text{(Eq 6)} \]

where \( C_{res} \) is the carbon residence in years, \( C_{i+1} \) total carbon stock in harvested wood-based products in year \( i+1 \) (+1 stays for the next year’s storage), and Outflow the total Carbon outflow released from harvested wood-based products to the atmosphere in year \( i \). Because the C stock development in this study setting follows an exponential increase trend until the saturation point, the relative differences between scenarios in Carbon residence also increase over time towards saturation point. Thus, we used average C stock and average outflow from a longer estimation period of 100 years instead of specific year selection to calculate the C residence.

2.5 Impacts of increased cascading on the avoided carbon loss from roundwood harvest

In some of the cascading scenarios (CASred), the demand for harvested roundwood is decreased due to cascading impacts. To assess the carbon emission reduction, i.e., climate change mitigation potential in the form of negative emissions, of different wood utilisation patterns, it is necessary to simultaneously account for both the technosystem and ecosystem GHG flows [3]. We additionally consider the avoided carbon loss from roundwood harvest
due to increased cascading of wood-based products, based on the carbon content of harvested roundwood. More detailed assessment of forest ecosystem carbon sink dynamics is out of the scope of this study. The avoided carbon loss from roundwood harvest is calculated as a material flow difference (t of C) in the cascading scenarios compared to the reference.

2.6 Overall avoided emissions compared to the Reference

The overall avoided emissions were calculated as the difference between a cascading scenario and the Reference scenario for the sum of the substitution impacts of wood-based products (see section 2.3) and the carbon stock change in wood products (see section 2.4). The Reference scenario portrays the current practice of using discarded sawnwood products for energy.

Additionally, we analysed the overall avoided carbon emissions when including the avoided carbon loss from roundwood harvest, calculated as the difference of the harvest level between a scenario and the baseline. In this case, the overall avoided emissions were calculated as the difference between a cascading scenario and the reference scenario for the sum of substitution benefits, carbon stock change in harvested wood-based products, and the avoided carbon loss from roundwood harvest (see 2.5).

3 RESULTS

3.1 Average substitution impacts and carbon residence

Table 3. The mean C residences in a 100-year calculation period and production structure weighted DFs with current and future DF assumptions.
The production structure-weighted C residence and DF values represent the middle results of this study, yet give a general overview of the average climate performance across scenarios (Table 3). CASplus had the highest performance in C residence (9.7 years) and production volume-weighted DFs (0.54 tC / tC and 0.25 tC / tC) (Table 3). Although CASred05 and CASred10 resulted in longer C residence (9.45 and 9.18 years) compared to Reference (9.04 years), CASred20 reduced the residence to 8.63 years due to total lower C stock in the technosystem (in harvested wood-based products). The total harvested carbon is lower in the CASred scenarios, because the raw material input is lowered by 5-20% for final products.

The cascading scenarios resulted in from 4% up to 8% higher production-weighted DFs compared to the Reference scenario (0.50 tC / tC and 0.21 tC / tC), since the cascading production results in additional substitution benefits without extra harvesting. We included future DF assumptions (2050 values) to the analysis to demonstrate a possible situation, where there would be fewer emissions to be substituted. In this case, the production structure weighted DFs are significantly lower when measured with 2050 assumptions, and cascading resulted in fewer substitution benefits.
3.2 Impacts of cascade use on the total substitution and carbon stock change of harvested wood products compared to the Reference

Table 4 shows the cascading impact on annual substitution and the annual average C stock change across selected calculation periods. All cascading scenarios, except CASred20, in which cascading production led to a 20% decrease in sawmilling product volumes, resulted in higher annual substitution compared to Reference (Table 4). CASplus had the highest wood-based product volume in total, thus also resulting in the highest avoided C emissions in terms of substitution compared to the reference, with 0.53 MtC/a more avoided emissions. On the contrary, in the CASred20 scenario the total substitution was 0.33 MtC/a less than Reference, because there were fewer wood-based products produced overall. The results showed a similar trend to 2050 DF assumptions. Casplus scenario resulted in 0.46 MtC/a more avoided emissions in terms of substitution compared to Reference, and CASred05 resulted in 0.34 MtC/a and CASred10 in 0.22 MtC/a, respectively. In CASred20 the avoided emissions in terms of substitution were lower compared to the reference (-0.02 MtC/a).

The average carbon stock changes also depend on the volumes in the technosystem. Thus, the cascading resulted in a greater annual average carbon stock change (positive net stocking) only in the CASplus scenario compared to Reference, when the average calculation period was 10-30 years (Table 4). In the 50-year calculation period, CASred5 also resulted in 0.01 MtC/a more avoided C emissions in terms of annual average carbon stock change, compared to the Reference. In the CASplus scenario there were 0.11 MtC/a more avoided emissions. CASred10 scenario had approximately the same amount of avoided C emissions in terms of annual average carbon stock change compared to the Reference over the 100-year calculation period, whereas in the CASred20 scenario there were still fewer avoided emissions than in the Reference.
Table 4. Avoided emissions in the cascading scenarios compared to the reference. The avoided emissions include annual substitution impacts (avoided fossil carbon emissions) with 2016 and 2050 DF assumptions, and annual average C stock change (biogenic C) with calculation periods of 10-100 years.

|                | Average annual C stock change (MtC/a) | Total annual substitution impact (MtC/a) |
|----------------|---------------------------------------|----------------------------------------|
|                | 10-year period | 30-year period | 50-year period | 100-year period | 2016 DF values | 2050 DF values |
| Reference      | 3.87          | 2.69           | 2.18           | 1.45           | 6.29           | 2.62           |
| CASplus        | 0.03          | 0.08           | 0.11           | 0.14           | 0.53           | 0.46           |
| CASred05       | -0.11         | -0.03          | 0.01           | 0.07           | 0.31           | 0.34           |
| CASred10       | -0.25         | -0.15          | -0.09          | 0              | 0.10           | 0.22           |
| CASred20       | -0.53         | -0.37          | -0.28          | -0.14          | -0.33          | -0.02          |

3.3 Impacts of cascade use on overall avoided carbon emissions compared to the Reference

Overall avoided carbon emissions in the technosystem include both substitution impact and carbon stock change. When the overall avoided C emissions in the cascading scenarios are compared to the Reference, the CASplus and CASred05 scenarios result in more avoided C emissions (0.2-0.67 MtC/a) over all C stock change calculation periods (Figure 2). In the CASred10 scenario, there are more avoided C emissions (0.1 MtC/a) than in the Reference only over the 100-year calculation period. The CASred20 scenario results in 0.47 - 0.86 MtC/a less avoided emissions than the Reference over all C stock calculation periods. With the estimates of 2050 DFs, where decarbonisation of non-wood sectors was assumed, the trend in the comparisons was similar (Figure 3). However, with 2050 DFs the CASred10 scenario resulted in more avoided C emissions (0.07-0.13 MtC/a) even with annual average C stock change calculation periods of 30 and 50 years.
**Figure 2.** Avoided C emissions (MtC/a) in the cascading scenarios (see 2.2.) compared to the reference including i) the annual total substitution (avoided fossil emissions) with 2016 DF assumptions and ii) avoided carbon loss in the technosystem (annual average of C stock change), with average of 10-100 year periods.

**Figure 3.** Avoided C emissions (MtC/a) in the cascading scenarios (see 2.2.) compared to the reference including i) the annual total substitution (avoided fossil emissions) with 2050 DF
When avoided carbon loss from reduced roundwood harvest was included in the comparison of overall avoided carbon emissions, all cascading scenarios resulted in more avoided C emissions than the Reference (Figure 4,5). With DF2050 estimates, CASred20 scenario would, unlike the technosystem comparison, result in the most avoided carbon emissions compared to the Reference (Figure 5). This is because the additional substitution impacts of material cascading would be significantly lower compared to current substitution impacts. The main benefits would result from avoided C emissions resulting from longer carbon storing periods instead of avoided fossil emissions resulting from substitution.

Figure 4 Avoided C emissions (MtC/a) in the cascading scenarios (see 2.2.) compared to the reference including i) the annual total substitution (avoided fossil emissions) with 2016 DF assumptions, ii) annual average of C stock change calculated with range of 10-100 years, and iii) avoided carbon loss due to reduced harvest (biogenic C) based on scenario-specific harvest levels.
Figure 5. Avoided C emissions (MtC/a) in the cascading scenarios (see 2.2.) compared to the reference including i) the annual total substitution (avoided fossil emissions) with 2050 DF assumptions, ii) annual average of C stock change calculated with range of 10-100 years, and iii) avoided carbon loss due to reduced harvest (biogenic C) based on scenario-specific harvest levels.

4. DISCUSSION

In this study we analysed the impact of increased cascading use of wood on avoided carbon emissions in Finland. Cascading of wood here refers to recycling discarded sawnwood products into panels and composites, instead of using them for energy generation. In this setting, we used explorative cascading scenarios to assess the carbon stock change of wood-based products and their substitution impacts, and avoided carbon loss from roundwood harvest, in comparison to current wood-based production- and end-use market structure impacts.

When including only technosystem impacts, the CASplus scenario, in which cascading increased the total volume of wood-based products, offered the greatest climate benefits in terms of combined impact of carbon stock change in harvested wood products and substitution compared to the Reference. However, when including avoided carbon loss from round-
wood harvest to the analysis and comparison, the results were more equivocal. Considering current product-level DFs and average C stock change taken from a 10- to 30-year calculation period, the CASplus scenario still resulted in the greatest avoided carbon emissions (equivalent to 2.18 – 2.34 Mt CO2) compared to the Reference. However, cascading scenarios (CASred) in which sawnwood product volumes were decreased 5-20% and consequently less roundwood was harvested, resulted in the most overall avoided carbon emissions (up to 2.97 Mt more reduced CO2 emissions per year) compared to the Reference, when longer (50-100 year) carbon stock change average calculation periods or future DF estimates were used. With future (2050) DF assumptions, most of the avoided carbon emissions originated from the decreased roundwood harvest and carbon stock change of harvested wood-based products. With future (2050) DF assumptions including the decarbonisation of non-wood sectors, the technosystem benefits decreased in terms of substitution, and the avoided carbon emissions gained from carbon stock change in harvested wood products and avoided carbon loss from roundwood harvesting played a larger role in overall avoided C emissions.

The impacts of wood cascading on ecosystem carbon flows have previously been considered more relevant than direct impacts on the technosystem [15,37]. Unharvested wood does not translate directly into 1:1 avoided carbon emissions as presented in this study. According to Kalliokoski et al. (2019) [34], a unit of harvested ton of wood equalling one ton of biogenic CO2 decreased forest carbon sinks on average 1.21 – 2.29 t CO2/ t CO2 between 2010 and 2055 in Finland, depending on the wood demand scenario. Applying these findings to our results, the avoided C emissions from decreased harvest would increase. The CASred05 scenario for instance, would avoid C emissions from decreased harvest 1.39 – 2.62 Mt CO2 in the short term (44 years) when compared to the Reference. In the CASred10 and CASred20 scenarios the decreased C emissions would be 2.77 – 5.24 Mt CO2 and 5.54 – 10.49 Mt CO2, respectively. However, this does not apply if disturbances such as forest fires or insect attacks
occur, thus harvested wood-based products may offer steadier carbon storage. On the other hand, long-term carbon storage in harvested wood products is not guaranteed either, as it depends on markets, which may change rapidly. Jarre et al. (2020) [35] have identified political incentives/barriers and market mechanisms as two of the most crucial factors that impact the realisation of wood cascading. Market regulation and supportive incentives for long-lifetime products and cascading practices ensuring efficient material use before energy use could improve the stability of carbon benefits in the technosystem.

In most comparisons, the Reference scenario resulted in more avoided C emissions through carbon stock change than the cascading scenarios (CASred) in which cascading production was assumed to substitute for primary solid wood products. It is obvious that fewer benefits are gained through wood utilisation in cases where are fewer wood-based products causing them overall. However, in the CASred05 scenario, the cascading decreased sawnwood production volumes only 5%, thus still resulting in 2.1%-3.6% more avoided C emissions than the Reference over all calculation periods and DF assumptions. The respective impact on avoided C emissions compared to the reference was from -6.5% to 0% for CASred10, and -13.7% to -7.0% for CASred20. The negative change implies less avoided C emissions gained than in the Reference. This was expected, since the higher reduction of sawnwood production volumes affected the production volumes of other products significantly as well, through sawmilling side stream utilisation. In addition, when sawnwood production volumes decreased, there was less potential material for cascading in the end-of-life stage. Thus, cascading use of a wood product as a substitute for a traditional wood product at market-level may lead to a counter effect in cascading potential at the production level.

The CASplus scenario, where cascading production increased the total production of forest-based industries and did not affect primary production, resulted in 0.8% - 9.5% (0.13-0.51 Mt
CO$_2$) more avoided C emissions due to carbon stock change in wood-based products compared to the Reference scenario. Budzinski et al. (2020) [17], found similarly that the emission reduction potential for material cascading in terms of lifetime extension of German wood products was approximately 0.04% (0.35 ± 0.06 Mt CO$_2$eq). Alam et al. [23] found that the changes in the lifespan of wood-based products substantially affected their mean carbon stock and the mean residence of wood-based products, and decreased net carbon emissions up to 8% compared to the reference life spans. Brunet-Navarro et al. (2017) [36] concluded that the half-life of a product has a slightly greater effect on carbon stocks than cascading itself. In their study the avoided C emissions under the current use of wood products in Europe in 2030 could be increased by 5 Mt CO$_2$ if an average lifespan was increased 19.54 % or if the recycling rate increased 20.92 % in 2017. These might not be separate issues either, as the aim of cascading is often to increase the lifespan of wood products. The comparison of the results of this study to other results is not directly feasible due to e.g. scenario differences, cascading volume assumptions, varying calculation methods and half-life assumptions. However, the results indicate that, in general, the lifetime extension of a product due to cascading can contribute to greater avoided biogenic C emissions through carbon stock change, when it does not substitute for other primary wood products, but the potential might remain modest depending on the cascading volumes and product-specific lifetimes.

CASplus scenario resulted in 8.4% (2.04 Mt CO$_2$) more avoided C emissions in terms of total annual substitution, compared to Reference. This was expected since the cascade use created additional substitution benefits without any additional wood harvest. On the contrary, when cascading led to decreased production volumes of sawnwood products through market substitution in the CASred scenarios, the results varied from +4.9% (1.09 MtCO$_2$eq./a) to -5.3% (-1.26 MtCO$_2$eq./a) compared to reference. The results were similar when future DF assumptions were used, but the impacts of cascading were less radical as the product level DFs were
closer to zero and differences thus smaller. If GHG emissions decreased in the non-wood sectors, the carbon stock change in wood-based products could play a larger role in climate change mitigation than substitution, at least in cases where cascade use could substitute for primary wood products at the market level.

There are some limitations in this study setting, since the scenarios are theoretical and based on simplified assumptions to isolate the impacts of cascading and exclude volume- or other production structure-related impacts. Therefore, it should be noted that the results cannot be interpreted as an assessment of the current situation, but rather as the relative magnitude of cascading impact compared to the case where material cascading does not occur. Another limitation is that cascading production was not assumed to consume extra energy in production, nor possible indirect impacts in lifetimes e.g. due to possible additional maintenance. In reality, these indirect impacts may hinder the positive impacts of assumed lifetime extension in cascading practices [13,17]. Additional energy demand in the cascading production could have decreased the substitution benefits in cascading scenarios. However, as the total energy needed in the cascading practices depends greatly on transportation distances and waste management technologies, quantifying that demand would require more detailed analysis and assumptions regarding future development. Importantly, this study did not quantify the indirect impact of changing harvest levels on the forest ecosystem carbon sinks. Including the forest ecosystem sink impact would have made the relative changes between scenarios greater, but not affected the rank order of the assessed scenarios.

One central aim of the paper was to model the net C impacts of cascading in light of two opposite market responses. Current models and data remain limited in their ability to address the issue of substitution, particularly in the context of new wood-based products, which is why which of the two market responses would prevail remains a matter of speculation. This repre-
sents a significant knowledge gap not only for assessing the various market responses within
the sector, but also for assessing the substitution impacts of wood use in general.

5. CONCLUSIONS

The study found that the impact of increased cascading on the avoided carbon emissions of
the forest sector are sensitive to the assumptions regarding average substitution impacts and
the market responses to increased cascading. However, the overall impact of cascading on the
climate change mitigation potential of wood use would appear to remain modest, although
non-trivial.

The results suggest that material cascading can result in 1.6%-5.4% more avoided C emis-
sions compared to the energy recovery of discarded wood products, when considering substi-
tution impacts, the carbon stock changes in wood products, and avoided carbon loss from
roundwood harvest. The ranking of different cascading scenarios depends on the time period
selected for the annual average calculation of the carbon stock change and DFs used (current
vs 2050 estimates). Without considering the avoided harvest of primary wood, the impact of
increased cascading is the smallest in cases in which cascaded products substitute for primary
wood products. The potential to avoid carbon emissions is higher in the short term if the ma-
terial cascading does not decrease the harvest levels but increases the total amount of wood-
based products in the technosystem. However, the opposite holds if the average substitution
impacts decrease significantly in the future. These findings could change if cascade use leads
to increased market uptake of lower DF- or short-lifetime products or heavily substitute for
long-lifetime products that are also a source for later material cascading. However, e.g.
Budzinski et al. (2020) [17] indicated that a decrease in lifetimes due to cascading does not
necessarily neutralise the climate benefits, and lifetimes should decrease for all considered products by at least 60% to have an opposite effect.

In light of these results, in the long term a more promising mitigation strategy than substitution could be to extend carbon residence in the technosystem, and cascading offers one means to this end. Possible solutions could combine market incentives to promote long-lifetime products and lifetime extension.

6. DECLARATIONS

6.1 Availability of data and materials

The data supporting this research are included within the article and its additional files: supplementary PDF documents A and B. The supplementary material can be requested from the corresponding author.

6.2 Competing interests

The authors declare that they have no competing interests.

6.3 Funding

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6.4 Authors' contributions

The researchers jointly designed the research objectives and methodology. Janni Kunttu collected the data and implemented the analysis with the help of co-authors. Janni Kunttu had the main responsibility of writing the manuscript, and the co-authors participated by editing and commenting the structure and forming conclusions.

6.5 Acknowledgements

Not applicable

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