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REPLY

Reply to Comment on 'Climate mitigation forestry—temporal trade-offs'

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Our recent study in this journal shows that reduced harvest can provide large and rapid climate benefits, which should be regarded as a means to reduce net CO_2 emission to the atmosphere the coming 20–30 years (Skytt *et al* 2021). The approach in the study is to examine how the carbon balance will be affected from varying harvest levels, given that today's usage and distribution of wood products will persist. Gustavsson *et al* (this issue) provide critical comments about our assumptions and methods. Here we show that many of the critical points are based on misconceptions or concern negligible carbon flows. However, Gustavsson *et al* also raise important questions of more general nature that deserve a more explicit discussion. Thus, we welcome this opportunity to clarify misunderstandings and discuss more general problems in this field. Gustavsson *et al* provide five main comments and we reply to each of them following the same structure.

(1) **Gustavsson *et al* claim that we 'place unfounded faith in the ability to quickly develop and deploy sustainable non-forest-based supply chains to respond to reduced forest harvest'**, arguing that reduced volumes of forest products will delay or prevent the introduction of new technology, referring specifically to bioenergy and carbon capture technology (CCS). However, CCS technology will likely be applicable to any point source of CO_2, being fossil or biogenic. Thus, it seems unlikely that reduced harvests will delay the development of CCS technologies. Another supporting argument by Gustavsson *et al* is that we set SF to zero for the electricity produced by the forest industry, which supposedly implies that we assume that the electricity production is already fully renewable. This is incorrect. We clearly state that the Substitution Factor (SF) for the electricity production exported to the grid is set to zero, because the industry in total consumes 21 TWh and produces is 6.5 TWh (Statistics Sweden 2020, pp 22, 34). This means that including the effect of electricity, which we choose not to, would lead to negative substitution. In other words, reduced harvest would lead to a surplus of electricity that can replace fossil fuels.

Gustavsson *et al* also claim that we underestimate the challenges for the introduction of new technology, referring to hydrogen for steelmaking, which they consider as 'immature technology'. However, the Swedish steel manufacturer SSAB has declared they will convert the blast furnaces in Oxelösund to an (electric) arc furnace by 2025, which will reduce their Swedish CO_2 emissions with 25% (SSAB 2021). We argue that a technology that will deliver significant CO2 reductions within 3–4 years cannot be considered immature.

(2) **Gustavsson *et al* claim that we do not consider the decreased production of pulp and paper when forest harvest is decreased.** This is a misunderstanding. We do consider the effects of reduced production of pulp and paper when harvests are decreased. This is explained in the methods part (Skytt *et al* 2021, ch 2). Avoided emissions are calculated using the substitution factors for pulp and paper given in figure 3, and the proportion of the carbon flow that goes to pulp and paper is provided in figure 2. The exact figures for the amount of carbon substituted is presented in the column headed 'sub. P&P' in the spreadsheet provided as supplementary

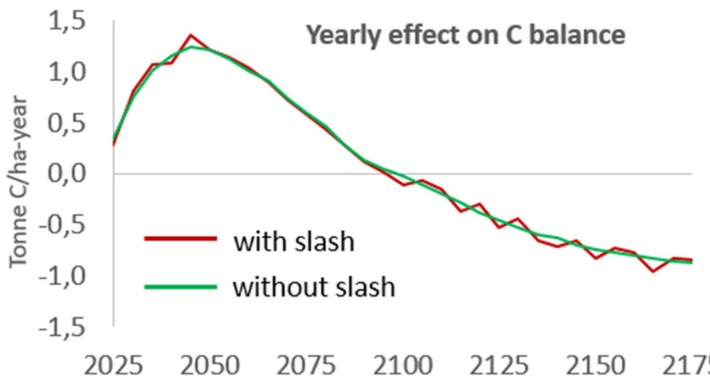

Figure 1. The yearly effect of slash harvest on the carbon balance of harvesting. The effect on the carbon balance is expressed as the difference between a no-harvest alternative and a business-as-usual alternative (BAU, 80% of growth), with or without slash harvest. A positive value means that the no-harvest alternative provide a larger uptake of carbon than the BAU alternative (Skytt *et al* 2021, figure 4(c)). The calculation concerns Gävleborg County in central Sweden and it is assumed that slash harvest is 3% of the total harvest. The variation in effect (red graph) comes from the variation in (automatic) slash outtake per period as calculated by the Heureka system (SLU 2021).

material. The substitution benefits are lower the lower the harvest level.

Gustavsson *et al* also claim that by ignoring avoided emissions from reduced harvest levels (which we did not do) we violate the LCA standard and 'fail to ensure functional equivalency by ignoring the services provided by pulp and paper products, which would decrease in step with decreased forest harvest'. This critique referring to violation of the LCA standard ISO14040/14044 is not valid, because our study focuses exclusively on the assessment of the environmental consequences of the use of wood on the macroscale. Thus, the functional unit definition does not apply (Jungmeier *et al* 2002, Cordier *et al* 2021).

(1) **Gustavsson *et al* claim that we apply SF for forest-based energy and materials that are low compared to current scientific evidence.** In our study we estimated substitution factors based on an extensive review of published studies, considering the usage of biomass for different product groups. A recent review that also estimates SFs based on actual usage, reported a weighted total SF in the range 0.22–1.16, which indicates that our weighted default SF of 0.95 is even somewhat high (Hurmekoski *et al* 2021).

Although Gustavsson *et al* do not refer to any scientific papers that find SFs higher than our default value, we note that studies by Gustavsson's *et al* (Sathre and O'Connor 2010, Leskinen *et al* 2018) report higher values. These studies present overall mean SF-values that are biased in the sense that they are based on data where substitution of construction material is overrepresented. Construction materials provide high substitution per mass used but represent a minor fraction of the total usage. The lion's share goes instead to products which show lower SFs. This is why studies weighting the substitution factors based on actual usage tend to find lower values than those applying an unweighted mean value of all published product specific SFs.

When arguing that we use too low SFs, Gustavsson *et al* also refer to our use of a SF of zero for electricity produced by the forest industry. Please refer to our reply to comment (1) above for a clarification.

We agree with Gustavsson *et al* that future SFs may increase. However, there are also valid arguments for decreasing SFs (Harmon 2019, Leturcq 2020). Our study is meant to be agnostic on this point and this is why we examine the effects of both higher and lower SFs.

(1) **Gustavsson *et al* note that we do not consider the climate mitigation potential of harvesting sustainable shares of forest residues.** This is correct, but the share of the total harvest is very small, and contrary to the claim made by Gustavsson, it has decreased during the latest years from 10.8 TWh 2013 to 7.9 TWh 2020 (Swedish Energy Agency 2021)[5] which correspond to 2.9% of the total harvest[6]. This is why we, for the sake of simplicity, excluded this and several other negligible flows (the use of fossil fuels for forestry machinery and transportation of timber are other examples). To demonstrate how slash harvest would affect the results, we have calculated the effect on the carbon balance of today's slash harvest level. Figure 1 shows that including slash harvest has an insignificant effect. The graph shows the climate benefit for a no-harvest alternative where the reference is either the original business-as-usual alternative (BAU, harvest 80% of the

[5] Data included from the database are slash and stumps (Swedish 'Grotflis' and 'Stubbflis').

[6] Assuming 0.408 ton DM m^{-3} (Skytt *et al* 2021) and 3 MWh/tonne harvested slash (Skogsforsk 2019).

growth according (see figure 4(c) in Skytt *et al* 2021) or BAU with addition of slash harvest[7].

(2) **Gustavsson *et al* claim that we do not consider the effects of climate change and the risk of disturbance to carbon stored in forest ecosystems.** We agree that there is an urgent need to improve our understanding of the direct and indirect effects of climate warming of the carbon sequestration in forests ecosystems. A moderate warming will most likely lead to increased productivity. Thus, we can use our analysis of regions with different productivity to see the qualitative effects of warming. Simply put, the direct effects of warming will be larger short-term benefits of reduced harvest, which will last for a shorter time. A more difficult question is how an increased frequency and severity of extreme weather events, fire and pests will affect the climate benefits of forestry. Today we lack models that can be used to provide such predictions. Thus, we think this critique is relevant but should perhaps be directed towards the entire field. This unfortunate situation is partly due to a lack of knowledge about how the effects of disturbances vary with forest management strategies. For studies using the Heureka system (SLU 2021) it is also a practical problem, as the current implementation of the software does not allow analyses of stochastic processes such as fire and extreme weather.

Gustavsson *et al* claim that we 'assume that unharvested forests will continue to grow and sequester carbon at a rate of 1.4–1.8 tC ha^{-1} yr^{-1} for 170–300 years, which is unrealistically high'. This is a misinterpretation of our text. It is explained at page 7 that 1.4 tC ha^{-1} yr^{-1} refers to the carbon sequestration predicted for 2025, and 1.8 tC ha^{-1} yr^{-1} is the peak level reached in 30 years. Over time carbon sequestration decreases as shown in figure 8.

1. Final remarks

A crucial aspect when modelling the climate benefits of forestry is what fractions of the harvest that provide substitution. Thus, we argue that a careful assessment of the different carbon flows is needed when evaluating the potential substitution benefits. Our strategy to assess this potential for different products is to ask: what will happen if the supply of biomass to the industry is decreased? If the answer is 'increased use of fossil fuels or materials', then there is substitution. However, if a reduction of the supply of biomass does not lead to increased use of fossil fuel and materials, then no substitution benefits should be accounted. Fractions of the harvest that provide no or reduced substitution according to our criteria include: losses in the paper and pulp industry (e.g. black liquor), material that end up in landfills without energy recovery, and the electricity produced by the forest industry. We are open to the possibility that there may be better criteria to use, but argue that the habit of routinely assuming that 100% of the harvest provide substitution is untenable. What fractions that provide substitution is as important as the choice of substitution factors and needs to be discussed with the same rigor.

Gustavsson *et al* promote high harvest strategies to obtain long-term climate benefits, even though such strategies result in large negative effects on the carbon balance during the coming decades. Reducing the harvests, on the other hand provide climate benefits the coming decades, which are considerably larger than all other emissions in the regions we studied (Skytt *et al* 2021, figure 4). However, we emphasize that a low harvest strategy should be continuously evaluated and adapted to the future development of substitution factors, forest growth and technical development.

[7] We simulated a no-harvest alternative and a business-as-usual alternative (harvest 80% of growth) for Gävleborg County using the Heureka system (SLU 2021). The BAU alternative was run with and without slash harvest. The settings for slash harvest was: slash harvest on maximum 55% of the final felling area, including stands with a minimum of 20% spruce and all soil moisture classes. These setting gave a slash harvest of 3% of the total harvest volume (calculated as carbon weight). 100% of the slash harvest carbon content was added as avoided emissions using the default SF for biofuel for each period. All other settings and calculations were made as described in Skytt *et al* (2021).

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