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Climate mitigation forestry—temporal trade-offs

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Abstract

The 1.5 °C target for global warming calls for evaluating short-term (30–50 years) climate change mitigation with different forests usage. In the current scientific literature and in the public debate, there are contrasting views on how forests should be managed to maximize total climate benefit, including the use of products and changes in carbon pools. Three major factors influence the conclusions in different studies: (a) time horizon, (b) site productivity, (c) substitution calculations. Here we show the dependency among these factors by an analysis of four harvest scenarios: 95%, 60%, 40% and 0% of growth, which are compared to a business as usual scenario (80%). The analyses are made for five counties in Sweden, which covers a wide range in forest productivities, from 2.5 $m^3\ ha^{-1}\ yr^{-1}$ (north) to 11.5 $m^3\ ha^{-1}\ yr^{-1}$ (south).

The results show:

(a) Reduced harvest levels provide increased climate benefits on short time scales (at least 50 years).
(b) Increased harvesting from current level is counterproductive on both short and long term.
(c) The potential effect on the carbon balance of a no-harvest scenario in the five counties, is larger (1.1–16 times) than the expected emissions from all other anthropogenic activities until 2045.
(d) Short-term climate benefits of reduced harvesting are largest in highly productive forests. Smaller but more long-lasting benefits can be obtained by aiming at harvest reductions in less productive forests.
(e) Strategies focused on short-term benefits need to be adapted to the future development of substitution factors and forest growth. If substitution effects become higher, increased harvest levels will be beneficial after 2050 in high productive forests. However, if future substitution effects decrease, which is a plausible and desired development, low harvest strategies are preferred in both short- and long-term time perspectives.

We conclude that even moderate reductions of harvest levels would provide substantial climate benefits.

1. Introduction

Forest management in boreal regions traditionally works with long time perspectives, evaluating management strategies over one or more rotation periods (typically 50–150 years). In contrast, IPCC (2018) emphasizes the need for mitigation activities that provide large climate benefits over shorter time scales. The sequestration of carbon dioxide (CO_2) in growing forests, as well as the substitution of fossil-based fuels and products with woody biomass, is the focus of many climate mitigation strategies. The traditional long-term perspective therefore needs to be complemented by analyses of short-term effects.

Published studies range widely in conclusions about the climate benefits of different mitigation strategies, i.e. the relative contribution of increased sequestration and increased substitution effects. Knauf *et al* (2016a) present slightly negative short-term effects for lower harvest between different harvest scenarios, and show clear long-term climate mitigation with increased harvesting for the German region Nordrhein-Westfalen. Poudel *et al* (2012) and Gustavsson *et al* (2017, 2021)), concludes that high harvesting strategies for Sweden are clearly better than low harvesting strategies. Werner *et al* (2010) show positive short-term (50 years) climate mitigation for Switzerland with a 'reduced forest maintenance' scenario, with about 45% reduction of extracted wood, but concluded that this would not be a preferred strategy in a longer time perspective. Lundmark *et al* (2014), conclude that short-term increase of the standing volume would be more efficient than harvesting, as long as the standing volume continue to increase enough to overrun the effects of substitution. Studies for Finland show reduced harvest volumes are preferred from a climate mitigation perspective (Seppälä *et al* 2019, Soimakallio *et al* 2021). Leturcq (2020) claims that wood material substitution effects are clearly overestimated and emission reductions are thus marginal, and that increasing harvest levels cannot provide climate mitigation. A review by Moomaw *et al* (2020) concluded that the carbon storage in natural forests is much higher than the storage in managed forests and products.

Studies focusing on long-term effects tend to find a preference for high harvest scenarios, and the long-term positive climate effects of increased harvests are often presented as a decisive argument, even when it is found that decreased harvesting levels provide short-term climate benefits (Lundmark *et al* 2014, Gustavsson *et al* 2021). Consequently, one source of disagreement about the most efficient climate mitigation strategy is how to view the trade-off between short- and long-term effects.

Another source of disagreement is the potential of harvested volumes to provide climate benefits through material and fuel substitution. When calculating carbon balance effects for forest products, substitution factors (SFs) are used to express benefits as tonne fossil carbon substituted per tonne biogenic carbon in the final product (tC/tC). A positive substitution occurs when woody biomass replaces other materials/products/energy and such replacement results in lower fossil-based CO_2 emissions (Smyth *et al* 2017, Leskinen *et al* 2018). However, there is considerable uncertainty about the expected climate benefits from substitution, partly because the underlying life cycle analyses vary in a range of critical methodological aspects (Sterman *et al* 2018, Hudiburg *et al* 2019, Peñaloza *et al* 2019), and partly because it is unknown how substitution effects will develop over time. Recent studies have noted that substitution benefits will likely decrease in the near future, as new strategies to reduce the use of fossil sources are developed (Knauf *et al* 2016a, Harmon 2019). An illustrative example is the Swedish project HYBRIT (Hydrogen Breakthrough Ironmaking Technology), aimed at a new process that eliminates direct emissions of CO_2 from steel manufacturing (SSAB 2021). If this process can be implemented, the consequence will be a drastic reduction of substitution effects by using wood for construction. Hence, there is considerable uncertainty about current SFs, and even more so about future factors. We conclude that there is no scientific consensus for how to perform substitution calculations, why results from different studies are hard to evaluate and compare.

This means that the evaluation of the climate change mitigation obtained by different harvesting strategies involves complex temporal trade-offs and large uncertainties that must be accounted for in policies aiming to maximize climate benefits. In particular, it is important to base policies on knowledge about the magnitudes of short- and long-term benefits, as well as the duration of short-term effects. In this study, we show that the relative magnitude of short- and long-term effects of harvesting are modified by forest productivity, harvest levels, and assumptions about substitution benefits. This is done by modelling changes in carbon pools and potential avoided emissions due to substitution, for five geographical regions representing a fourfold range in productivity. The results enhance our understanding of how site conditions and model assumptions affect the results of forest management evaluations.

2. Method

Here we provide a brief description of the methods and data sources. For further details, see the supplementary material (available online at stacks.iop.org/ERL/16/114037/mmedia). Our method to calculate the effect on the carbon balance from different harvest strategies involved the following steps (see also figure 1):

(a) Simulate forest growth and decomposition for different harvest scenarios per county to estimate changes in total forest carbon stock, including carbon in living and dead trees, as well as soil.
(b) Map current wood flow from harvest to final product, to identify volumes that provide substitution.
(c) Establish Substitution Factors, SF, from literature for each final product (from point (b)) and calculate weighted substitution effects per product group.

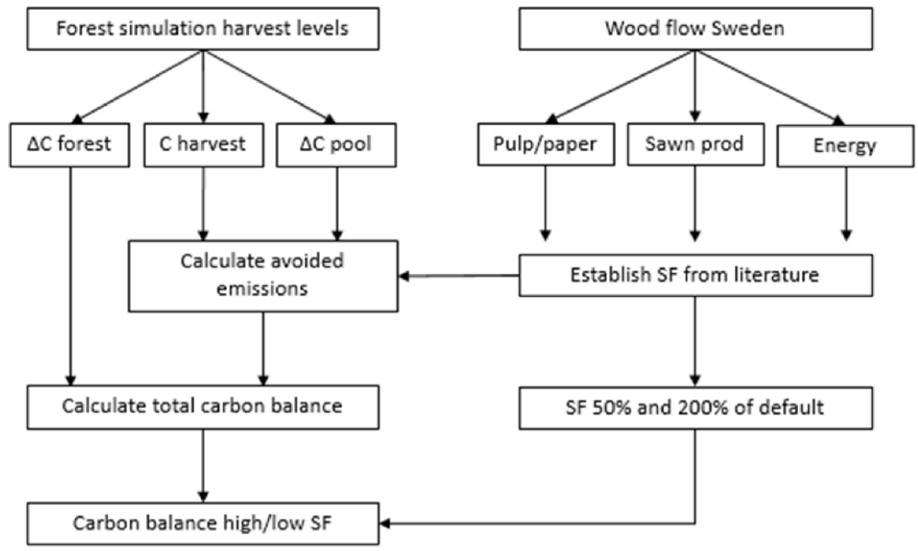

Figure 1. Method as a simplified overview. Note that the method is based on the use of 'avoided emissions' per harvest scenario. This means that harvest alternatives will give avoided emissions of fossil-based carbon, in proportion to the harvest level and changes in the product carbon pool. For the wood flow and SF calculations, see figures 2 and 3.

Table 1. The studied counties. Lat = latitudinal range (see figure 4). Mean temp = mean annual temperature during 1991–2020 (SMHI (2021b). Forest area = productive forest area (1000 ha). Standing volume = stem volume over bark from stump to tip. Site productivity = productivity in cubic metre standing volume per hectare and year. Age = mean age of standing volume in years (SLU 2020). BAU = current proportion of growth that is harvested (Swedish forest agency 2021, SLU 2021b). The mean values for the five counties (except "Forest area" which is the sum of the county areas) given in **bold** and the corresponding values for Sweden in *italics*.

County (Country)	Lat (S to N)	Mean temp	Forest area (kha)	Standing volume (m^3 ha^{-1})	Site productivity (m^3 ha^{-1} yr^{-1})	Age (yr)	BAU (share of growth harvested)
Norrbotten	65°1′ N 69°1′ N	0.5 °C	3930	110	2.49	138	50%
Jämtland	61°8′ N 64°2′ N	2.2 °C	2682	140	3.32	116	70%
Gävleborg	60°2′ N 62°3′ N	5.0 °C	1486	154	5.70	61	80%
Västra Götaland	57°1′ N 59°3′ N	7.5 °C	1292	205	8.92	66	80%
Skåne	55°3′ N 56°5′ N	8.6 °C	416	193	11.55	54	85%
Mean for five counties		**4.8 °C**	**9806**	**141**	**5.00**	**101**	
(SWEDEN)	*55°3′ N 69°1′ N*	*4.9 °C*	*23 550*	*151*	*5.24*	*89*	*80%*

(d) Calculate the total effect on the carbon balance per forest harvest alternative, including substitution effects, and changes in the product pools for long-lived wood products.
(e) Perform a sensitivity analysis by setting a low SF (from step (c)), and a high SF and calculate corresponding total effects as in step (d).

When establishing relevant SF for step (c), there is a large (and growing) literature to consider. We performed an extensive review to identify factors for different final products. In step (d) we followed the Production Approach specified by IPCC for how to calculate stock changes in the product pools (IPCC 2019, p 12.44). In step (e) we established a low and a high SF from our default values, to explore the level of uncertainty in our assumptions. To investigate the effects of forest productivity, we ran simulations of forest growth and soil carbon dynamics for five Swedish counties that cover a productivity gradient from 2.49 to 11.55 cubic metre stem volume per hectare and year (table 1).

2.1. Forest modelling

The different forest management alternatives were simulated during 200 years in the *Heureka RegWise* forest modelling software (SLU 2021a) using data from the Swedish National Forest Inventory 2014–2018 (SLU 2020) to describe initial conditions such as species composition, forest age, and

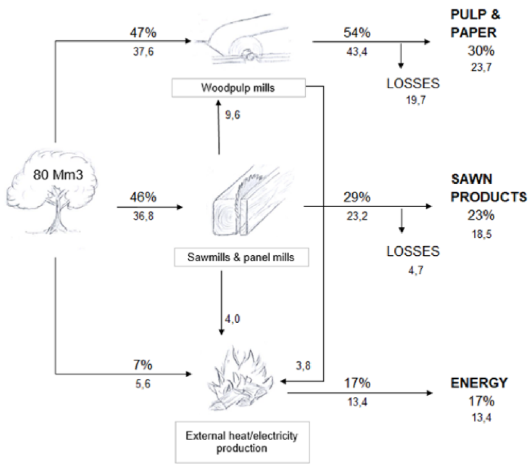

Figure 2. Wood production flow in Sweden 2019 used as a base for all counties. Shares of the input are given as percentage and volumes in Mm^3. (Statistics Sweden 2020a, Swedish wood 2021, Swedish forest industries 2021, Swedish forest agency 2021).

site productivity. Post-harvest regeneration is done within three years from harvest with tree species suitable for the site soil conditions to maximize forest productivity. Pre-commercial thinning and thinning are performed in accordance with best practice. For each county, six different harvesting alternatives were simulated on land classified as productive forestland, applying even-aged management. Since no forestry activities are allowed on formally protected areas in Sweden, these areas were set off as unmanaged in all alternatives and will thus be neutral between alternatives. As reference scenario we used the Swedish mean harvest level during 2010–2019, which corresponds to 80% of the growth (table 1). This scenario, henceforth referred to as business-as-usual (BAU), was compared to the following harvesting scenarios: 0%, 40%, 60% and 95% of growth. The harvested volumes were divided into three product groups, using total flow proportions for Sweden (figure 2). The proportions are assumed to be constant and independent of the harvest volumes.

The Heureka system provides a detailed representation of Swedish forest dynamics, and it is widely used in advanced forest growth calculations in Sweden. Still, there are important aspects that are not included, such as effects of rot root, bark beetles and defoliators, and wildfires, which may reduce growth in both young and old forests (Sharma *et al* 2013, Piri and Valkonen 2013). Additional uncertainty stems from the growth models, implemented in Heureka; they are considered accurate in a 50 year perspective (Fahlvik *et al* 2014), but the uncertainty increases for longer simulation periods. We did not use the built in climate change model available in Heureka because it was considered too simplistic (see supplementary material).

2.2. Substitution calculations

Estimating SF requires complete life cycle assessments (LCAs) for each product alternative. The need for consistent and transparent LCAs is obvious (Peñaloza *et al* 2016, Seppälä *et al* 2019), but the large variety of product types and the wide geographical range over which the substitution takes place for exported products, make this task in principle impossible. Hence, to identify SF for each of the three major product groups, we performed a review of a basket of commonly cited studies, and extracted SFs for 14 product types matching the Swedish product mix. SFs for each of the three major product groups ($\overline{\mathrm{SF}}$) were then calculated as a weighted mean of the sub-product types: $\overline{\mathrm{SF}} = \sum_i p_i \mathrm{SF}_i$, where p_i is the share of the total flow and SF_i the substitution factor for sub-product i given in figure 3.

We address the uncertainty through a simplified sensitivity analysis where default values are halved and doubled (table 2), respectively. The derived SF interval 0.5–1.9 covers most studies without including extreme estimates. The low SF value might be used to reflect future scenarios if current SFs have decreased (Knauf *et al* 2016a), whereas the high SF value can be relevant if SFs should increase over time (Schladminger and Marland 1996).

Not all biomass provides substitution. In our study we applied a principle recommended by e.g. Sathre and Connors (2010) and Leskinen *et al* (2018), and included only cases where a decrease of the supply of biomass to the industry would lead to increased use of fossil fuels or materials. This means that products lacking fossil-based alternatives, such as graphic paper, only provide substitution as end-of-life combustion. Other fractions not providing substitution are the biomass used for energy in the paper and pulp industry (see section 4) and the electricity produced by the paper and pulp industry. The latter follows from the fact that the Swedish forest industry uses more electricity than what is produced (21 TWh vs 6.5 TWh in 2019 (Statistics Sweden 2020b, pp. 22, 34)). Since both the electricity consumption and production are expected to be approximately proportional to the harvest volumes, lower harvest volumes will cause decreased demand for electricity, rather than increased use of fossil fuels. The industry as such is thus not contributing to electricity production since the difference between production and consumption is clearly negative.

2.3. Carbon pool dynamics

Stock changes have been calculated according to the production approach recommended by IPCC, which means that we accounted for the export but not the import (Brown *et al* 1998, p 20 ff).

Sawn products were classified as long-lived, with a half-life (exponential decay) of 35 years (IPCC 2019, p 28) and 80% of the wood lost from this

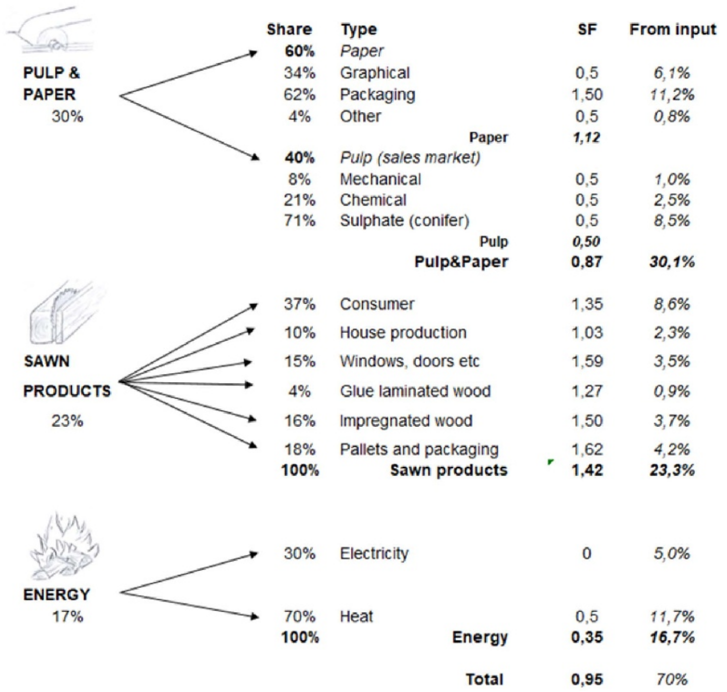

Figure 3. Substitution factor per product type from a breakdown of the major product groups (pulp&paper, sawn products and energy) from figure 1. The column 'SF' states substitution factors for each product type based on a basket of studies (see supplementary material). SFs for packaging and impregnated wood could not be identified from literature, but was set to a value just below pallets and packaging. The SF values for the three major product groups are weighted means of the SFs for the sub-product types in each group. Product volumes/shares were obtained from (Statistics Sweden, Swedish wood 2021, Swedish forest industries 2021, Swedish forest agency 2021).

Table 2. Substitution factors per product group; default, low and high. Only one decimal as given in this table has been used when calculating avoided emissions.

Type	SF default (tC/tC)	Low SF (50%)	High SF (200%)
Pulp&Paper	0.9	0.5	1.8
Sawn prod.	1.4	0.7	2.8
Energy	0.4	0.2	0.8

product pool was assumed to substitute fossil fuels as end-of-life energy recovery (see supplementary material). Pulp&paper products were classified as short-lived (lost within five years, which is the temporal resolution of the simulation) and we assumed 100% recovery rate to substitute fossil fuels. Biomass for energy was also classified as short-lived, being combusted within five years.

To provide context we related short-term carbon balance changes until 2045, to total emissions from anthropogenic sources as forecasted per county until 2045 (Persson 2018, Andersson *et al* 2019, Länsstyrelsen Gävleborg 2019, Länsstyrelsen Jämtlands län and Region 2019, Sardén *et al* 2019). In this case the effects of reduced harvests were calculated as differences between no harvest (0%) and the observed mean harvest volume per county during 2010–2019 (50%–85% of the growth, table 1).

Results are presented as 'Effects on carbon balance' with positive values as uptake of carbon from the atmosphere, and negative values as emissions. To estimate the actual effect on the climate, radiative forcing has to be calculated from the carbon balances. For CO_2 (and other greenhouse gases) the radiative forcing until a specific time is not the same as the current atmospheric CO_2 content (Levasseur *et al* 2016). However, to facilitate comparisons with other studies we follow common praxis and report effects as changes in the net transport of carbon to the atmosphere. The effect on the carbon balance was calculated as the difference between a harvest alternative and the Swedish BAU 80%. If the balance is positive the harvest alternative results in an uptake compared to the national BAU. Cumulative carbon balances are the accumulated carbon uptake for a specific harvest alternative until a specific year. The contribution to the carbon balance from substitution was recorded as 'avoided emissions', which for reduced-harvest scenarios meant lower values than in the BAU scenario. Conversely, in the high harvest scenario (95%) we recorded more avoided emissions than the BAU scenario.

3. Results

Reduced harvest volumes, compared to the 80% harvest baseline, provide a short-term positive net effect on the carbon balance in all counties studied. However, the magnitude and duration of this effect vary with forest productivity, harvest levels (figure 4) as

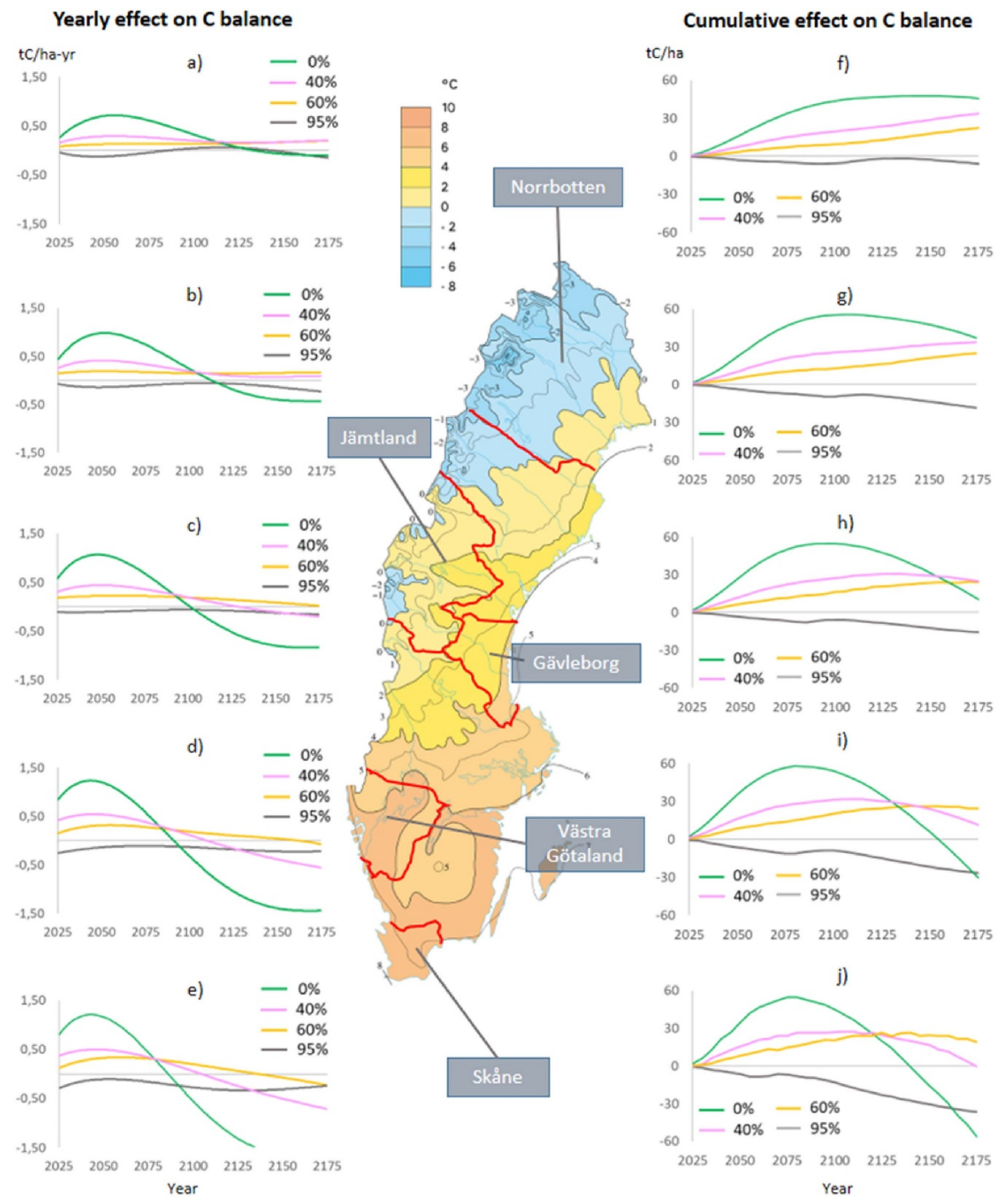

Figure 4. Effects on the carbon balance for five counties in Sweden, covering a gradient in productivity (see table 1). The map shows the location and borders (red) of the counties, and yearly mean temperatures for the period 1961–1990. Graphs (a)–(e) show the yearly effect on the carbon balance per harvest scenario expressed as the difference between the harvest scenario and the reference scenario (harvest 80% of the growth) (4th degree polynomial smoothing). A negative balance means that the 80% alternative gives a higher benefit. A positive balance means the 80% harvest alternative gives a lower benefit than the alternative. Graphs (f)–(j) show the cumulative effect on the carbon balance per hectare for the same scenarios as to the left (no smoothing applied). The temperature map is reproduced with permission from SMHI (2021a).

well as substitution effects (figure 7). Annual effects on carbon balances (figures 4(a)–(e)) of increased harvests do not show positive outcome compared to 80%. In contrast, reduced harvest levels provide short-term positive effects that increase with increasing forest productivity. The long-term effects are opposite to the short-term effects; the lower the harvest level, the lower the carbon uptake.

The cumulative effects during 150 years, representing both short-term and long-term effects (figures 4(f)–(j)), show that the 0% harvest levels provide the largest positive balance effect for the entire 150 year period in the two northernmost counties (figures 4(f) and (g)). This also holds in the more productive counties in central and southern Sweden (figures 4(h)–(j)) during the first

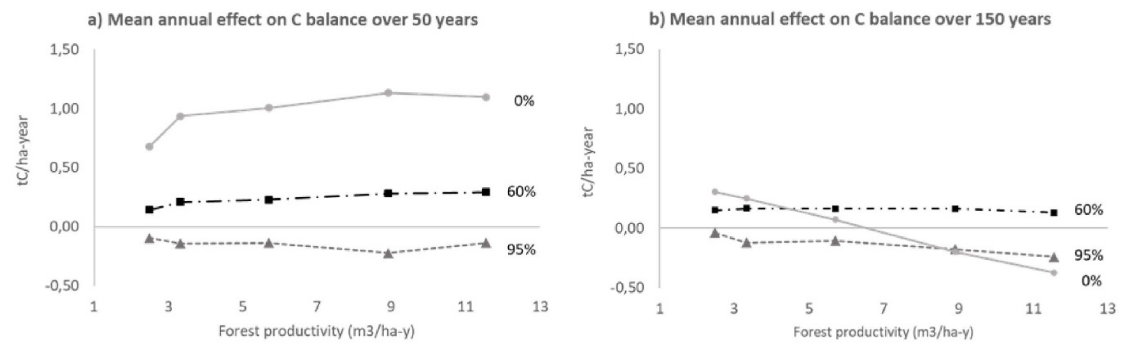

Figure 5. Annual mean effect on the carbon balance (tonne carbon per hectare and year) across forest productivities and harvest alternatives; 95% of growth, 60% of growth and 0% relative the baseline national BAU (80%). Each data point represents a county with its specific forest productivity (see table 1). The productivity (x-axis) follows the temperature gradient from north (left) to south (right). Figure (a) shows mean annual effects over 50 years (2025–2075) and (b) over 150 years (2025–2175).

100–140 years, after which the 40% and 60% levels provide the most positive effect. For the higher forest productivities (figures 4(i) and (j)) the 40% alternative peaks after about 100 years. From a short-term perspective (10–50 years), the carbon balances increase with decreasing harvest volumes. From a forest productivity perspective, the short-term carbon balance is more positive for high productivity forests (figures 4(c)–(e)) than for low productivity forests (figures 4(a) and (b)). Although the carbon balance from reduced harvest levels is lower for low productivity forests than for high productivity forests, it takes longer to obtain a positive carbon balance from increased harvest levels.

These effects are summarized in figure 5, showing the mean annual effect on the carbon balance per hectare along the productivity gradient, when evaluated over 50 years and 150 years. In the 50 year perspective, lower harvest levels and higher productivity provide more positive carbon balance effects (figure 5(a)). In the 150 year perspective, the 60% harvest level gives a more positive balance than the 0% level, if the forest productivity is above 3–4 m^3 ha^{-1} (figure 5(b)). If the productivity is above 8–9 m^3 ha^{-1}, the 95% harvest alternative also gives larger uptake than the 0% harvest alternative, but still show lower effects than the 60% harvest levels across all productivities.

To put the short-term carbon balance effects into a broader context, figure 6 shows the predicted mean annual anthropogenic emissions from other sources per county until 2045, relative to the short-term carbon balance of the 0% harvest alternative. Here the effect of the 0% harvest alternative was calculated as the difference from county specific BAU-levels (see table 1). The uptake of carbon are as large or much larger (1.1–16 times higher) than all other anthropogenic emissions in these counties.

The analysis of the effects of low and high SF, highlight the importance of taking the uncertainty of SF into account. Assuming low SF further supports the general conclusion that reduced harvest levels provide clear positive effects on the carbon balance.

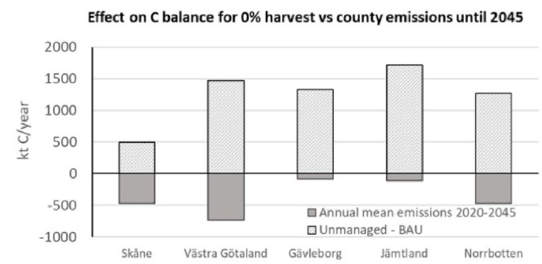

Figure 6. Annual emissions per county and year (negative), compared to the potential carbon uptake if the current harvesting (county specific BAU) is replaced by a no-harvest alternative (0%) until 2045.

High SFs mainly shifts the timing when a positive effect on the carbon balance occurs from harvesting. Figure 7 shows the effect on the carbon balance for different harvest levels for high SF, in (a) and (c), and low SF, in (b) and (d), for Skåne and Norrbotten respectively. On a short-term basis, the low harvest strategies show a positive effect on the carbon balance compared to high harvest strategies, regardless of high or low SF. With high SFs, high productivity forests (a) provide an annual net positive effect on the carbon balance with BAU compared to 60% harvest level after about 50 years, while it takes about 150 years with low SFs. The positive effect on the carbon balance with a low harvest strategy in Norrbotten lasts longer according (c) and (d) but the difference between the alternatives is smaller than for the high productivity forests in Skåne. If SF is low, the short-term carbon uptake with a low harvest strategy is larger, the higher the forest productivity (see also graphs in supplementary material).

The temporal trade-off, comparing short-term and long-term effects on the carbon uptake, has a base in the total carbon sequestration in the forest. Figure 8 shows total carbon sequestration in the forest per hectare and year if the forests are left unmanaged (0% harvest). The higher the forest productivity, the higher the short-term peak for the

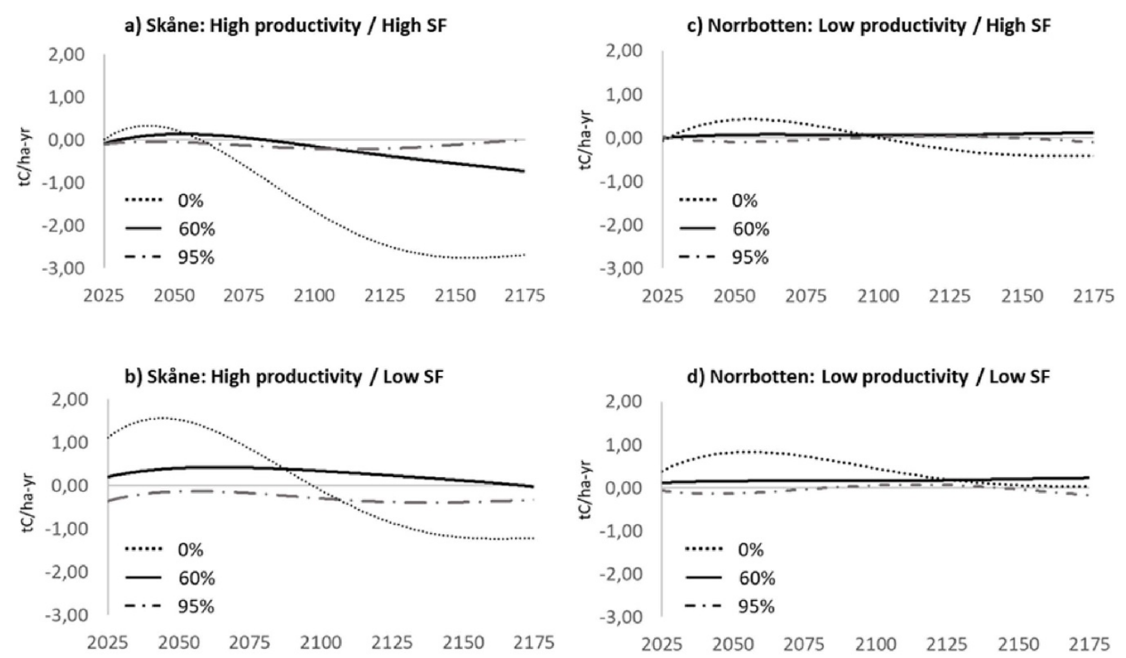

Figure 7. Annual effects on carbon uptake (tonne carbon per hectare and year) for Skåne (South Sweden, (a) and (b)), representing high forest productivity and Norrbotten (North Sweden, (c) and (d)), representing low forest productivity, applying either high or low subsitution factors for the 150 year period 2025–2175 for three different harvest levels; 0%, 60% of growth, 95% of growth compared to the baseline scenario (national BAU 80%).

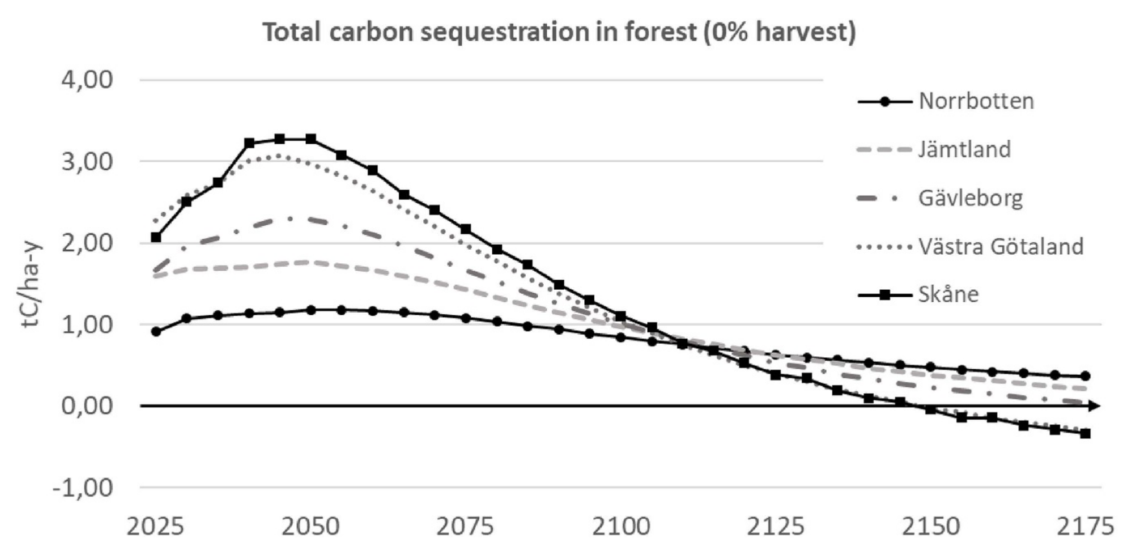

Figure 8. Total carbon sequestration in the forest per county (tonne C per hectare and year) if the forests are unmanaged during the simulated period 2025–2175. Negative values mean that the forests emit carbon and positive values indicate sequestration of carbon. The graphs only show the forest carbon pools (soil carbon, carbon in living biomass, in stubs and roots, as well as in dead wood).

carbon sequestration (around 2045) ranging from 1.2 tC ha^{-1} yr^{-1} (Norrbotten) to 3.3 tC ha^{-1} yr^{-1} (Skåne). According to the Heureka growth models, the net carbon sequestration in the forests ceases after 120–200 years from today, except for Norrbotten (lowest site productivity). The weighted average growth for all five counties is today 1.4 tC ha^{-1} yr^{-1} and peaks at 1.8 tC ha^{-1} yr^{-1}. Note that this predicted future sequestration is for the current average forest age in the different counties (table 1). Hence, carbon sequestration is predicted to continue for 170 years (Skåne) up to 300 years (Norrbotten), if the forests are left unmanaged.

4. Discussion

By analysing different counties in Sweden, we highlight how the expected effects on the carbon balance of different harvest levels depend on forest productivity, the temporal perspective, and assumptions about substitution. Based on these analyses, we conclude that reduced harvest levels provide significant and rapid climate mitigation. Only from a long time perspective can current or higher harvest levels provide climate benefit.

Reduced harvest levels provide larger short-term positive effects on the carbon balance the higher the forest productivity, whereas the effects are smaller, but longer lasting, for low productive forests. From a very long-term perspective, high harvest levels might be preferred in productive forests. However, even in a 100 year perspective, low harvest strategies still show more positive cumulative effects than high harvest strategies. To counteract the long-term decline in growth if low harvest strategies are used, harvest volumes might have to be slowly increased over several periods to find the optimal harvest level.

These temporal patterns are largely determined by changes in the forest carbon pools that occur after harvest. The short-term benefits of reduced harvest arise because harvesting leads to an immediate reduction of carbon uptake and increased decomposition. The long-term benefits of increased harvest levels occur because the carbon uptake in the regrowth will eventually become larger in managed forests than in old unmanaged forests.

Assumptions about substitution also modify these patterns. Assuming high substitution effects means that short-term benefits of reduced harvesting become smaller and last for a shorter time, whereas low substitution effects means higher and more long-lasting effects. Moreover, there is an interaction between substitution and forest productivity. As shown in figure 7(a) the combination of high substitution and high productivity decreases both the duration and the magnitude of the short-term benefits, potentially providing long-term benefits of increased harvest.

Different effects of forest productivity and substitution likely explain some of the conflicting conclusions reached in studies of harvesting effects on the climate benefit. The short duration of climate benefits of reduced harvest in high productive forests combined with assumptions of high SFs, may motivate recommending high harvest strategies (Gustavsson *et al* 2017, Poudel *et al* 2012, Gustavsson *et al* 2021).

However, it is important to note that calculated total substitution effects also are determined by factors other than the actual SF. The product mix, especially the proportion of the harvest that is used for high substitution products, may explain why e.g. Knauf *et al* (2016a), studying the region Nordrhein-Westfalen in Germany, found no short-term benefits with reduced harvesting. The fraction of the harvest that is used for substitution is also critical. Chen *et al* (2014) assumed that only 64% of the sawn products used for the Canadian construction market actually replaced non-wood materials in buildings, which indicates the need to investigate to what extent different product groups provide substitution. It is only in cases where reduced use of wood products lead to increased future use of fossil-based products or fuels, that avoided emissions can be accounted (Sathre and O'Connor 2010, Leskinen *et al* 2018). An illustrative example is the use of by-products from paper production, such as black liquor, as fuel in the same process. Although these by-products once replaced fossil fuels, and it is conceivable that the reverse may happen in the future, it is not likely that reduced supply of biomass to the paper mills would lead to increased use of fossil fuels today. Rather we should expect that lower harvest volumes lead to reduced production of pulp&paper and thus lower use of energy.

Werner *et al* (2010) studying Switzerland, found short- to medium-term benefits of reduced harvesting, but concluded that this benefit will not be accounted for according to the Kyoto-protocol. Furthermore, they point at the risk for future forest collapse. Soimakallio *et al* (2021) and Seppälä *et al* (2019) present results for Finland also showing benefits with reduced harvests in line with our results. The mean forest productivity in Finland is similar to the productivity in Sweden, and SFs set are in line with the SFs identified in our study. They have, similar to us, not implemented any activities modifying the future productivity which may result in different conclusions as in (Gustavsson *et al* 2017, 2021). However, effects of increased productivity, through management or positive climate effects, are captured in our analysis through the large productivity gradient analysed.

When considering the relative value of short- and long-term effects on the carbon balance it is important to consider the uncertainty associated with long-term effects. One important source of uncertainty is the future SF. It has been suggested that SFs will increase as new products are developed (Schladminger and Marland 1996), but more recent studies argue that decreasing SFs is a more likely development (Knauf *et al* 2016a, Harmon 2019). The ambitious goals stated in the Paris agreement is now affecting international and national strategies and legislation and the EU (2021) aims at being climate-neutral by 2050 with net-zero emissions of greenhouse gases 2021. A likely consequence of this development is that available products will have decreasing carbon footprints, thus reducing the scope of future substitution. This implies that strategies relying on long-term growth predictions and high SF, will be based on the assumption that national and international goals will not be reached.

A second source of uncertainty is how well the models represent the growth in old forests. The Heureka system was developed with a focus on traditional rotation forestry and the data used when developing growth models includes few really old stands. Long-term predictions should thus be treated with caution. For example, recent studies suggest that old forests are carbon sinks rather than sources

(Besnard *et al* 2018), which questions the model results shown in figure 8. Yet, the Heureka models are the currently best available tool to predict future forest growth in Sweden.

It is worth noticing that the estimated short-term positive effects on the carbon balance are considerable and even moderate reductions of harvest levels would compensate a substantial part of the total emissions of fossil carbon in the analysed counties. This means that forest management strategies can be used to buy us the time needed to implement sustainable technical systems, such as non-fossil fuel based electricity production, carbon capture and storage etc.

5. Conclusions

The scientific disagreement about which harvest strategies that maximizes climate mitigation, reflects different assumptions about substitution effects, differences in forest productivity, and to what extent short-term and long-term effects are considered. Our study focus on strategies to increase the short-term climate benefits of forestry, by considering carbon uptake in forests and products, as well as substitution effects of harvested volumes.

We draw the following major conclusions for climate change mitigation forestry from our study:

(a) Reduced harvesting from current level provide short term climate benefits.
(b) Increased harvesting from current level is counterproductive on both short and long term.
(c) The potential positive effect on the carbon balance that can be obtained from reduced harvest levels in the five counties studied, is considerable compared to the emissions of fossil carbon from other anthropogenic activities. This can be used to buy us time to implement sustainable technical systems.
(d) Short-term carbon balance benefits can be achieved by focusing on harvest reductions in highly productive forests. Smaller but more long-lasting benefits can be obtained by aiming at harvest reductions in less productive forests.
(e) Strategies focused on short-term benefits need to be continuously evaluated and adapted to the future development of SFs and forest growth. If substitution effects become considerably higher, increased harvest levels might be beneficial after 2050, if forest productivity is high. If future substitution effects decrease, which is a plausible and desired development, low harvest strategies are preferred from a carbon balance perspective in both short- and long-term perspectives.

Given the urgent need to provide climate mitigation in the coming 10–30 years we suggest that future research should focus on forest management strategies that can provide rapid climate benefits. Reducing harvest levels is indeed a measure that do provide large and rapid mitigation, and it requires no challenging technical developments. However, there are alternative methods that may be more attractive from an economical point of view, such as reduced thinning, prolonging rotation periods, increasing fertilization, and developing harvesting schemes optimized for carbon mitigation. The full mitigation potential of these measures requires further studies. We also see a need for a harmonized methodology for how to calculate substitution effects, preferably formulated as IPCC guidelines. Finally, we see a need to develop forest growth models that accounts, not only for temperature changes into consideration, but also for annual expected distribution of precipitation, changes in decomposition rates, and expected effects of pests, fires and storms.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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