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PAPER

Climate change mitigation from increased paper recycling in Sweden: conserving forests or utilizing substitution?

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Abstract

Climate change mitigation by increased paper recycling can alleviate the two-sided pressure on the Swedish forest sector: supplying growing demands for wood-based products and increasing the forest carbon sink. This study assesses two scenarios for making use of a reduced demand for primary pulp resulting from an increased paper recycling rate in Sweden, from the present 72% to 78%. A *Conservation* scenario uses the saved primary pulp to reduce pulplog harvests so as to increase the forest carbon sink concomitant with constant overall wood product supply. In contrast, a *Substitution* scenario uses the saved primary pulp to produce man-made cellulosic fibers (MMCF) from dissolving pulp replacing cotton fiber, implying increased overall wood product supply. Our results suggest that utilizing efficiency gains in paper recycling to reduce pulplog harvests is better from a climate change mitigation perspective than producing additional MMCF to substitute cotton fiber. This conclusion holds even when assuming the use of by-products from dissolving pulp making and an indirect increase in MMCF availability. Hence, unless joint improvements across the value chain materialize, the best climate change mitigation option from increased paper recycling in Sweden would seemingly be to reduce fellings rather than producing additional MMCF.

1. Introduction

The climate change mitigation potential of the forest-based sector is primarily based on the ability of forests to sequester carbon dioxide (CO_2) from the atmosphere and store it in its soils and biomass including storage in harvested wood products (HWPs) (EC 2021b). This potential can be complemented by (i) the substitution effect, i.e., potentially reduced greenhouse gas (GHG) emissions resulting from replacing more emission-intensive products and energy with wood-based alternatives (Hurmekoski *et al* 2021), and (ii) the feasibility and degree of recycling and use of recovered wood products (Lorang *et al* 2022).

Sweden is the second largest roundwood supplier in the European Union (EU) and has the largest forest area, 28 Mha (EUROSTAT 2024). At the EU level, two principally contrasting views on forest management exist to improve the forest sector's contribution to climate change mitigation. On the one hand, programs such as the EU Green New Deal aim to increasingly rely on bio-based resources - implicitly implying intensified forest management - in order to further substitution (EC 2021b). However, the highly intensive forest use in Sweden leaves little room for further increasing harvest rates (SCB and SLU 2023). On the other hand, other policy initiatives such as, notably, the EU's land use, land use change and forestry (LULUCF) regulation aim for strengthening the natural forest carbon sink (EC 2023). This poses a two-sided pressure on the Swedish forest sector in contributing to climate change mitigation.

One option for alleviating this conflict is increased circular wood use in the form of improved circularity and resource efficiency. This can either be achieved by aiming for long cascading use, e.g., timber frame becoming particleboard at the end-of-life, the latter being energy recovered when disposed (Thonemann and Schumann 2018), or through recycling of wood fiber for producing the same material again, e.g., wastepaper being recycled into recovered pulp which itself can replace primary (virgin) pulp in papermaking.

Paper and paperboard are the most recycled materials in Europe (CEPI 2022) and their utilization in form of recovered pulp is the most common wood product recycling process today (Lauri *et al* 2021). In the EU, the overall paper recycling rate was 71% in 2021 (EPRC 2022b) and in the same year it amounted to 72% in Sweden (FTI 2023). By 2030, the paper industries in the EU consider themselves ready to take circularity to a new level and endeavor to reach a 76% paper recycling rate (CEPI 2022), which is close to 78%, the maximum rate considered achievable, due to non-collectable and/or non-recyclable paper products such as hygiene papers (EPRC 2022a). Challenges to paper recovery are on the one hand reduced consumption of paper grades commonly recycled at high rates, e.g., graphic paper, and on the other hand increased demand for more complex paper products, such as technical papers, which require specialized recycling processes (EPRC 2022a). The remaining potential in increased paper recycling in the EU and Sweden in parallel with the pressures and expectations on the forest sector to reduce global warming, thus provokes the question how such an efficiency gain could best be used to mitigate climate change, reconciling the aforementioned contrasting policy objectives.

Within the EU, Brunet-Navarro *et al* (2017) state that increasing paper recycling would be a viable short-term climate change mitigation measure. On the product-level this was formerly found by Merrild *et al* (2009) highlighting the climate change mitigation effect from potential substitution credits as consequential to saved primary wood being used otherwise. Still on the EU level, Bais-Moleman *et al* (2018) confirmed a GHG reduction potential from jointly increasing recycling of paper and waste wood to a technical maximum rate relative to current practices. Lorang *et al* (2022) studied the climate effects of increased paper recycling on a national scale for France, by adding the recycling industry to an existing forest sector model. Climate effects from increased paper recycling were found to be highly dependent on whether primary and recycled pulp are considered perfect or imperfect substitutes. A slight climate benefit was given for perfect substitutability, i.e., a 1:1 replacement, and additional emissions given complementarity. For the Swedish forest sector however, the effect of additional paper recycling and use of recovered wood products remains rather undiscovered in climate impact assessments, while two contrasting options exist for potential climate change mitigation.

The first option implies using the recovered pulp over primary pulp to reduce pulplog (in the following synonymous with pulpwood) harvests in Swedish forests. The second option instead aims to use the saved primary pulp and thus the 'surplus pulplogs' (given unchanged harvest levels) to produce wood products with a high substitution effect potential such as textiles from man-made cellulosic fibers (MMCF) in form of viscose (Leskinen *et al* 2018). MMCF, today mainly produced from wood, account for about 6% of the global fiber market. Based on their technical properties MMCF sourced from wood can replace the more emission-intensive fibers made from cotton (Hurmekoski *et al* 2018) which currently dominate the global market together with polyester, holding shares of 22% and 54%, respectively (Leskinen *et al* 2018, Textile Exchange 2022, Hurmekoski *et al* 2023). Of the MMCF used for textile applications, viscose is most important with a dominant market share of around 80% (Textile Exchange 2022). The production of MMCF as well as global general fibers has for at least doubled since 1990 from 3 million tons (Mt) and 58 Mt to about 7.2 Mt and 113 Mt in 2021, respectively, and is foreseen to further expand due to projected increasing demand under a business as usual trend (Textile Exchange 2022). Substitution of the dominating, more emission intensive textile fibers polyester and cotton is thus seen as a major requirement for limiting global warming within the global textile industry, next to reducing overall growth in the sector (Textile Exchange 2022).

These two contrasting options for climate change mitigation mark the starting point for the present study, which aims to analyze the climate effects of an increased paper recycling rate in Sweden. Two scenarios based on the abovementioned options for how to utilize the additionally recovered pulp are defined, i.e., a *Conservation* scenario and a *Substitution* scenario. The overriding assumption in both scenarios is thereby a 1:1 replacement between primary pulp sourced from pulpwood and recovered pulp. The climate effects assessed are compared to a business-as-usual (BAU) reference, or baseline, scenario to account for the marginal change in the GHG balance. With the two climate change mitigation scenarios from increased paper recycling at hand, we set out to answer the research question '*Which is the best climate change mitigation scenario given an increased recycling of paper in Sweden - using recovered pulp to reduce fellings (of pulpwood) and thereby increasing the Swedish forest carbon sink, or producing MMCF to substitute for other textile fibers?*

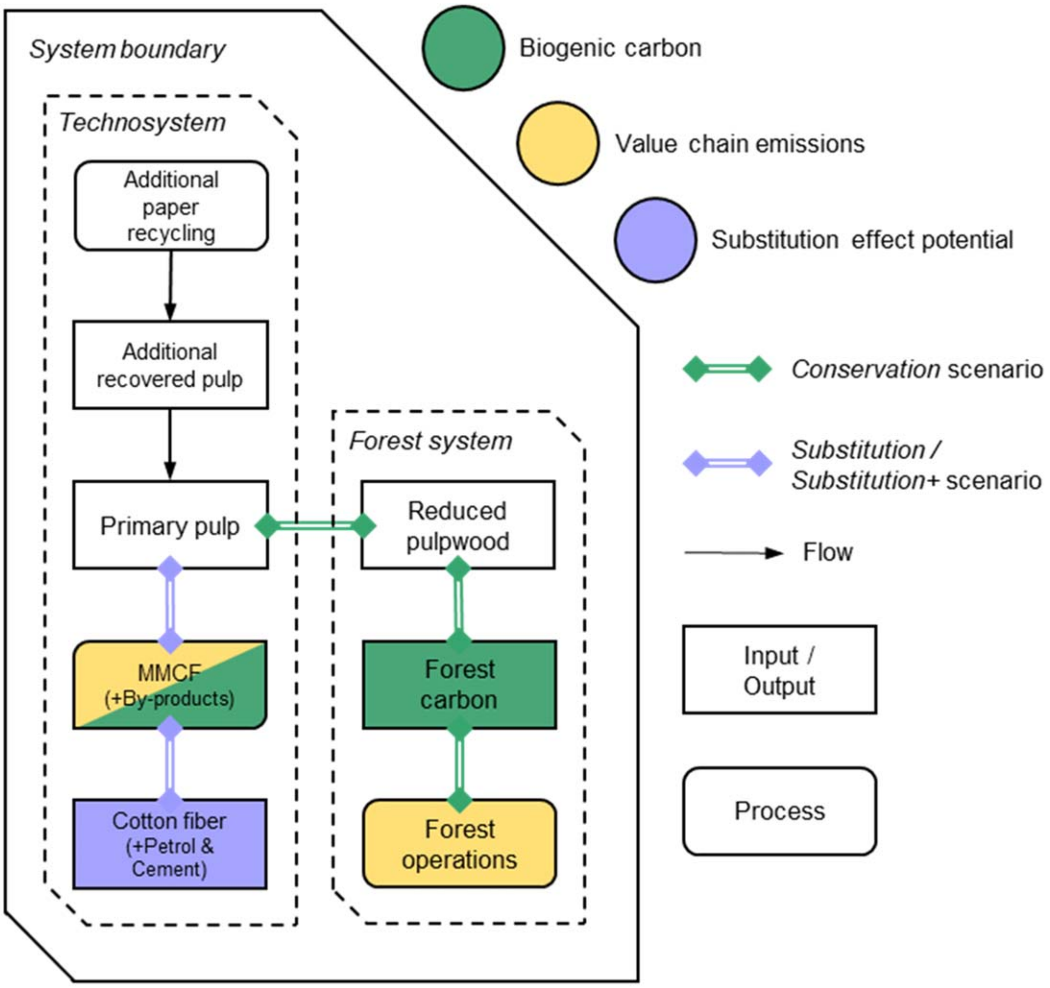

Figure 1. System boundary encompassing the marginal effects of additional paper recycling from the *Conservation and Substitution/ Substitution*+ scenario on the biogenic carbon and fossil greenhouse gas balances from value chain emissions and potential substitution effects within techno- and forest system.

2. Methods

2.1. System boundaries & scenario set-up

Figure 1 shows the system boundaries of the study as given for the two scenarios making use of the additional recovered pulp arising from increased paper recycling, compared to the BAU reference situation. The BAU reference is characterized by maintaining the present 72% recycling rate of paper products in Sweden (FTI 2023) and a constant production of pulplog-based wood products. The system boundaries are divided into a technosystem and a forest system. The technosystem is set in Sweden considering the additional paper recycling until the additional primary pulp making, and in China, where the substitution of cotton fiber at the point of yarn making is assumed to occur. The forest system is solely set in Sweden. Within the systems, the changes in GHG balances due to increased paper recycling are accounted for in terms of biogenic carbon in forest biomass, and fossil emissions from the forest industry and substitution effects, i.e. potentially avoided emissions. The time horizon spans 80 years from 2020 until 2100, to account for the short- and medium-term climate effects. The modelling of both scenarios departed from the increased paper recycling leading to additional recovered pulp, which is assumed to fully replace and thus save primary pulp in papermaking.

The *Conservation* scenario assumes that the amount of saved primary pulp leads to a decrease in pulpwood harvests. Consequently, the scenario includes biogenic carbon changes in the forest within standing biomass, dead wood, and soil organic carbon, as well as changes in the fossil GHG balance induced by decreased forest operations and increased fossil emissions from enhanced paper recycling and pulp recovery. The *Conservation* scenario assumes an equal quantity of supplied wood products compared to the BAU reference situation.

In the *Substitution* scenario, the saved primary pulp is used to produce MMCF. Accordingly, there are additional fossil emissions from increased paper recycling, as well as from increased production of dissolving pulp and MMCF. The additional supply of MMCF is assumed to replace cotton fiber whose saved fossil

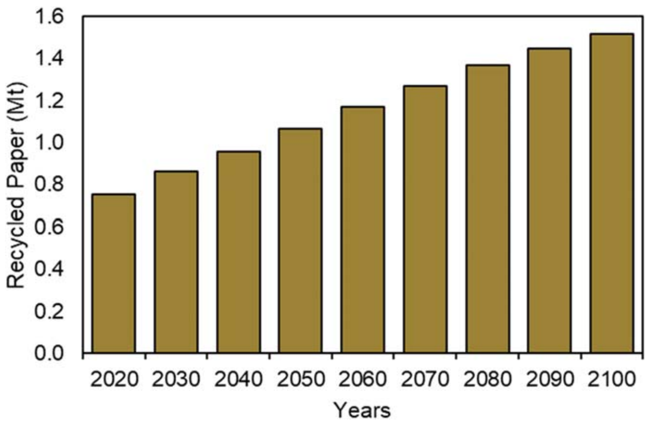

Figure 2. Projected recycled paper supply in Sweden from 2020 until 2100 under the business-as-usual (BAU) scenario, given in Mt.

emissions are considered as substitution effects. The substitution of cotton by MMCF is assumed to cancel out the additional biogenic carbon storage since this is similar among both fiber types. The fossil GHG balances are only accounted for from cradle-to-gate, since it is assumed that fossil emission differences between MMCF and cotton fiber appearing after the point of substitution, i.e., yarn making, from spinning, transportation to retailers, or end-of-life combustion, are similar (Lidfeldt *et al* 2022) and cancel out each other. The *Substitution* scenario assumes an increased supply of wood products as compared to the BAU reference or the *Conservation* scenario. By-products from the MMCF feedstock dissolving pulp production are considered to be used for internal energy recovery, i.e., no substitution effect arises from these. However, a sub-scenario of the *Substitution* scenario, in the following *Substitution*+ scenario, considers possible avoidance of petrol and cement due to further processing and use of the by-products, and accounts for potential substitution effects and additional biogenic carbon storage accordingly. A description of this sub-scenario is given in section 2.2.

A key feature of the study is that only relative climate effects are assessed, i.e., the GHG differences between the BAU scenario and the *Conservation* and *Substitution* scenario, respectively. Changes in the greenhouse gas balances and potential climate change mitigation arise solely from the consequence of an increased recycled paper quantity. Climate effects are stated as ‘additional’ compared to the continuation of the BAU reference. A ceteris paribus assumption applied to the system boundaries is that the provision of other products than pulp and pulp-based products, e.g., by-products from the sawmilling industry, are not affected by the increase in the paper recycling rate. We disregard the GHG implications in the remaining wood manufacturing sector producing sawnwood, plywood, panels, or fuelwood. This is in line with Lorang *et al* (2022) who found that the effects on emissions in other wood manufacturing sectors are minor or negligible.

The functional unit of the *Substitution*/*Substitution*+ scenario was the quantity of fiber produced given in Mt year^{-1}.

2.2. Modelling of the technosystem

At first, the BAU reference was defined. The modelling departed from the projection of recycled paper supply for Sweden from 2020 until 2100 as based on Global Biosphere Management Model (GLOBIOM) simulations under the absence of any representative concentration pathway (RCP) climate change model (Havlík *et al* 2018, Lauri *et al* 2021) as shown in Figure 2. The data on recycled paper supply were interpolated to annual values and converted into recovered pulp, using a conversion factor of 0.91 Mg Mg^{-1} (RISE 2022). Subsequently, the difference in recovered pulp among the BAU scenario (72% paper recycling), and either of the scenarios (78% paper recycling) constituted the ‘saved’ primary pulp quantity. The recovered pulp production ranged from placing the recovered paper into the pulper to the recovered pulp ready to be fed into the paper machine, where the point of substitution of the primary pulp by the recovered pulp was defined. Accordingly, the recovered pulp was not considered to be air dry but in a pumpable state. Substitute paper products from the recovered pulp, for which primary pulp was used before, were packaging grades (corrugated grades) for which no additional dispersing, deinking, or bleaching is required, which instead is often given for tissue papers or graphic papers that can also contain large shares of recovered pulp. The saved primary pulp quantity was subsequently converted into saved pulplogs (*Conservation* scenario) or MMCF replacing cotton fiber (*Substitution* scenario), based on the modelling steps displayed in Figure 3.

The *Conservation* scenario comprises converting the saved pulp quantity to pulplog equivalents and assessing the saved forest carbon. The pulplog quantity over bark, given in volume, is estimated by applying a conversion factor of 4.8 m^3 pulplog, under bark Mg^{-1} pulp (FAO 2020) and an over bark to under bark coefficient of

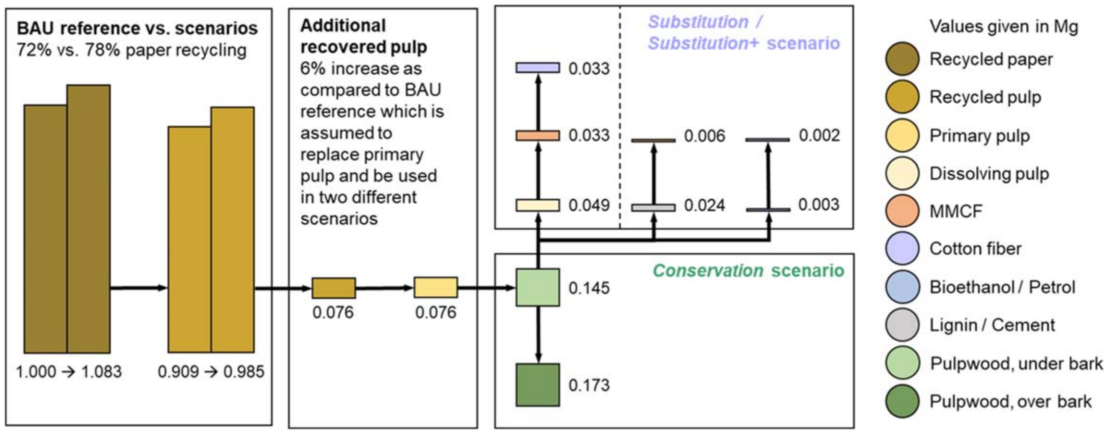

Figure 3. Conversion steps departing from the difference in recycled paper and recovered pulp between BAU reference and scenarios, ranging over additional saved primary pulp, the equivalent pulpwood quantity (Conservation scenario), the production of dissolving pulp and MMCF, substitution of cotton (Substitution scenario), as well as additional by-products and their substitutes petrol and cement (Substitution+ scenario), illustrated as based on 1 Mg of recycled paper under the BAU reference.

0.90 m^3 (FAO 2020). The result - the saved pulplog quantity given in m^3 over bark - was used to calculate the biogenic carbon implications in the forest system using the forest decision support system Heureka PlanWise (section 2.3).

Modelling the *Substitution*/*Substitution*+ scenario also entails converting the saved pulp quantity into equivalent pulplog volumes by applying conversion factors of 4.8 m^3 pulplog Mg^{-1} pulp and 0.90 m^3 under bark m^{-3} over bark, as for the *Conservation* scenario. The volume of pulplogs, over bark was converted into mass applying a density of 0.40 Mg m^{-3} (FAO 2020). The mass in pulplog equivalents was used to calculate the quantity of dissolving pulp, which could be produced from the saved pulp amount using a coefficient of 3.0 Mg pulplog Mg^{-1} dissolving pulp (Lidfeldt *et al* 2022). In Sweden, two major production sites exist producing dissolving pulp which is dedicated for MMCF. Domsjö mill (Domsjö Fabriker 2022) located in Västerbotten, northern Sweden, using both hard- and softwood, and Södra mill (Södra 2023) located in Blekinge, southern Sweden, which uses mainly birch hardwood. In this study, we based the modelling of dissolving pulp production on Lidfeldt *et al* (2022) and assumed the production to rely on softwood, as it is practice at Domsjö Fabriker (2022). Producing dissolving pulp from pulplogs results in the by-products hemicellulose and lignin, from the digestion process and bark. The *Substitution* scenario assumes to rest the fate of the by-products on internal energy recovery which is the general use in Sweden, and which does not lead to a substitution effect potential (Skytt *et al* 2021). The *Substitution*+ scenario, in contrast, assumes that the by-products are further processed, based on the practice at Domsjö Fabriker. Here, both by-products are derived after drying the washed wood feedstock. The by-product hemicellulose is mainly fermented in an ethanol plant to produce bioethanol serving as a biofuel to be blended with petrol in cars. Lignin, which is produced along the process of bioethanol making, is used as an admixture in concrete to improve its flow properties and strength characteristics thus reducing the need for cement in concrete structures. The yield ratio of the by-products per unit of dissolving pulp produced in 2022 was 7% bioethanol, and 49% dried lignin (Domsjö Fabriker 2022). Accordingly, the *Substitution*+ scenario accounts for bioethanol and concrete admixture, in terms of the additional biogenic carbon storage, as well as additional value chain emissions, and potential for substitution effects. A replacement ratio of 1:0.62 was assumed for bioethanol considering its lower heating value of 26.7 MJ kg^{-1} and that of petrol, 43.4 MJ kg^{-1}. For the lignin-based concrete admixture, a ratio of 1:0.25 with cement was assumed, based on a 25 weight percentage (wt%) of cement (Sutradhar *et al* 2023), while for the biogenic carbon storage in the lignin-based admixture a half-life time of 35 years, i.e., consideration of a 'long-lived' wood product, was assumed (Rüter *et al* 2019). After dissolving pulp is produced, it was modelled to be transported to central Asia, where the production of the MMCF viscose is assumed to occur. The transport was simulated by a bulk carrier marine vessel departing in Sweden with the destination of China, whose fossil emissions were based on NTMCalc 4.0 (NTM 2024). Viscose production was modelled based on Lidfeldt *et al* (2022). Table 1 summarizes the quantities of the required resources such as chemicals and energy for the production process with a yield ratio of 1.5 Mg dissolving pulp Mg^{-1} viscose. The mass of viscose given in fiber was assumed to replace for conventional cotton fiber, since technical properties and production processes of cotton are more similar to wood-based fibers, compared to polyester fiber (Hurmekoski *et al* 2018). Cotton fiber production was assumed as a global market average. The replacement ratio between viscose and cotton fiber was assumed to be 1:1, based on the mass ratios of the different textile fibers (1 kg viscose fiber replacing 1 kg cotton fiber).

Table 1. Inputs for MMCF production (Substitution/ Substitution+ scenario) given for 1 kg of viscose fiber, based on Lidfeldt *et al* (2022).

Inputs	Quantity	Unit
Dissolving pulp	1.5	kg
Carbon disulfide	0.062	kg
Chemical inorganic	0.011	kg
Electricity	2.535	MJ
Heat	3.447	MJ
Heat, other than natural gas	9.282	MJ
Sodium chloride	0.085	kg
Sodium hydroxide	0.501	kg
Nitrogen, liquid	0.032	kg
Oxygen, liquid	0.013	kg
Sodium hypochlorite	0.107	kg
Sulfur dioxide	0.141	kg
Sulfuric acid	0.048	kg
Zinc monosulfate	0.010	kg
Outputs	Quantity	Unit
Viscose fiber	1	kg

One sensitivity analysis was conducted on the *Conservation* and the *Substitution+* scenario to test the influence of the primary pulp to pulplog ratio (pp-ratio) by increasing or decreasing it by 20%, while primary pulp was assumed to be a perfect substitute for recovered pulp. The pp-ratio is thus the amount of pulplogs necessary to produce one ton of pulp. This affected the climate effects as consequential to, either changed pulplog saving potentials (*Conservation* scenario), or altered substitution effect potentials (*Substitution+* scenario). In addition a second sensitivity analysiswas performed on the *Substitution+* scenario altering the replacement ratio between MMCF and cotton fiber by ±20% to take account of a differing degree of substitution or complementation, respectively.

Life cycle inventory data for the dissolving pulp, and MMCF, i.e., viscose production, were based on Lidfeldt *et al* (2022) and the data for cotton fiber as well as all other underlying emission data were taken from the ecoinvent 3.9 database (Wernet *et al* 2016). See the Supplementary Material for details.

2.3. Modelling of the forest system

Biogenic carbon balances in Swedish forests were simulated for the BAU scenario and the *Conservation* scenario using the forest decision support system Heureka PlanWise version 2.22.0.0 (Lämås *et al* 2023), similar as done in Schulte *et al* (2023). For the *Substitution* scenario, this was not required since the biogenic carbon balance was the same as under the BAU scenario. The forest system was based on National Forest Inventory (NFI) data from 2020, limited to the productive forest land in Sweden where tree growth per ha and year is larger than 1 m^3, an area of around 24,000,000 ha. On the productive forest land, voluntarily and formally set-aside areas were excluded from the assessment. The mean wood volume on productive forest land equals 139 $m^3 ha^{-1}$ (excluding the nature reserves and set-aside lands) and the mean age at final felling throughout the past five-year average equals 100 years (SFA 2024a). The average annual harvest volume during the past five years (2017–2021) amounted to 93,240,000 m^3 over bark (SFA 2024b).

Computation of biogenic carbon in living trees was done using biomass expansion factors. For above-stump tree biomass these were based on Marklund (1988) and for stump and root biomass on models by Petersson and Ståhl (2006) while decay of coarse woody debris was based on Kruys *et al* (2002) and Sandström *et al* (2007). Soil organic carbon (SOC) calculation on mineral soils relied on the Q-model (Ågren and Hyvönen 2003), which computes continuous soil organic matter decomposition, and emission factors for peatland. Deadwood carbon was assessed with exponential decay rates from dead wood inflow following tree mortality (Harmon *et al* 2000). During the Heureka simulations, neither favourable nor detrimental effects of climate change on the forest were considered since the available tools in the software do not implement negative effects, i.e., increased occurrence of calamities. This does not permit a balanced assessment along with the availability of accounting for positive, i.e., growth enhancing, influences.

The reference forest carbon levels originated from the official Swedish forest impact analysis (Skogliga konsekvensanalys), in the following 'SKA', conducted by the Swedish Forest Agency on behalf of the government of Sweden and in collaboration with the Swedish University of Agricultural Sciences (SLU) (Eriksson *et al* 2022). Here the scenario 'dagens skogsbruk', i.e., 'business as usual' was chosen as it assumes to continue current forestry practices during the simulated time horizon. This concerns both land use (areas of nature conservation provisions, consideration areas and timber production land), as well as the management methods that are applied today, for example in terms of regeneration methods, choice of tree species and extent of fertilization and clearing. This scenario uses the same felling intensity (felling in relation to growth on timber production land) as during the 2011–2015 period, which corresponds to 79% of net growth (gross growth - natural decline) on timber production land.

Reference levels for national harvest projections of sawlogs and pulpwood were based on simulations of GLOBIOM under the absence of any RCP climate change model (Havlík *et al* 2018, Lauri *et al* 2021).

For the *Conservation* scenario, the reference harvest levels worked as the absolute benchmark against which the saved pulpwood harvest volumes were compared to. The saved pulpwood harvest was modelled by, e.g., reduced thinning intensities, or changed rotation lengths. The decreased harvest intensity, given in m^3, amounted to the relative forest carbon difference, given in Mg C, and constituted the climate impact occurring within the forest system given in biogenic CO_2.

2.4. Climate impact metrics

The assessment of the climate impact was done using the metric of global warming potential (GWP_{100}) and was complemented with the absolute global temperature change potential (AGTP) (Forster *et al* 2021). The AGTP accounts for timing of emissions, their perturbation lifetimes and associated atmospheric dynamics, which the GWP_{100} omits. It is expressed in degrees of kelvin (K) and equals the response in global mean surface temperature at a certain point in time due to a shift in radiative forcing from a GHG pulse emission, i.e., from CO_2, CH_4, or N_2O. Thus, AGTP enables assessments of time dependent dynamics of climate effects. Perturbation lifetimes of CH_4, and N_2O were 12.4 and 121 years, respectively, and that of CO_2 was based on the Bern carbon cycle model (Joos *et al* 2001), which simulates the molecule to remain airborne until it is taken up by either oceans or the biosphere. The AGTP is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H - t)\, dt \tag{1}$$

where radiative forcing (RF), expressed in W m^{-2}, and the climate response function (R_T) form a convolution over the assessed time horizon (H) induced from a change in RF due to a pulse emission of a GHG *x*. The term AGTP is used in the following synonymously with the term temperature change.

3. Results & discussion

3.1. Additional recovered pulp, savings in pulplog harvest, and increased MMCF supply

Figure 4 shows the additional recovered pulp amount as induced by the simulated increased Swedish paper recycling, to the rate of 78% as compared to the current 72%. The resulting annual average addition of recovered pulp amounts to about 0.09 Mt, which equals 0.8% of the annual pulp production in Sweden under 2022, 11.8 Mt (Swedish Forest Industries 2023). In terms of the *Conservation* scenario, this represents on average 0.42 Mm^3 pulplog equivalents per year to be saved from harvest over the entire time horizon of this study. Over the past five years, the average annual pulplog harvest volume in Sweden amounted to about 31.6 Mm^3 (SFA 2024b). The pulplog harvest savings found here accordingly represent about 1.3%, a decent saving potential when considering that the current supply of pulp-based products would remain constant.

Under the *Substitution/Substitution+* scenario, the 0.09 Mt annual average addition of recovered pulp led to an increase in dissolving pulp production of 0.03 Mt (using 'freed up' pulplogs). This equals a production increase of about 8% when considering the sum of dissolving pulp volumes produced at Domsjö Fabriker (2022) of 178,000 Mg and Södra of 155,000 Mg (Södra 2023) during 2022. In terms of additional MMCF, the increase amounts to around 0.02 Mt as an annual average. This represents only a very small addition—0.3% - compared to the global annual production of viscose, which was 5.8 Mt in 2021 (Textile Exchange 2022).

3.2. Climate change mitigation from increased paper recycling in Swe

3.2.1. Aiming for conserving forests or for utilizing substitution?

The cumulative GHG balance of the *Conservation* and *Substitution*/*Substitution+* scenario from 2020 to 2100 is displayed in Figure 5 where negative values indicate a benefit to the climate. Overall, either scenario induces a climate change mitigation effect, as compared to the continuation of the BAU reference, i.e., maintaining the current 72% paper recycling rate. This highlights previous findings that additional paper recycling, may be seen as a viable mean to reduce net GHG emissions within the forest-based sector, given an effective substitution of primary pulp by recovered pulp (Merrild *et al* 2009, Brunet-Navarro *et al* 2017, Lorang *et al* 2022). However, the *Conservation* scenario has a distinctly larger GHG mitigation potential than the *Substitution*/*Substitution+* scenario. The most effective climate change mitigation from increased paper recycling in Sweden found here is

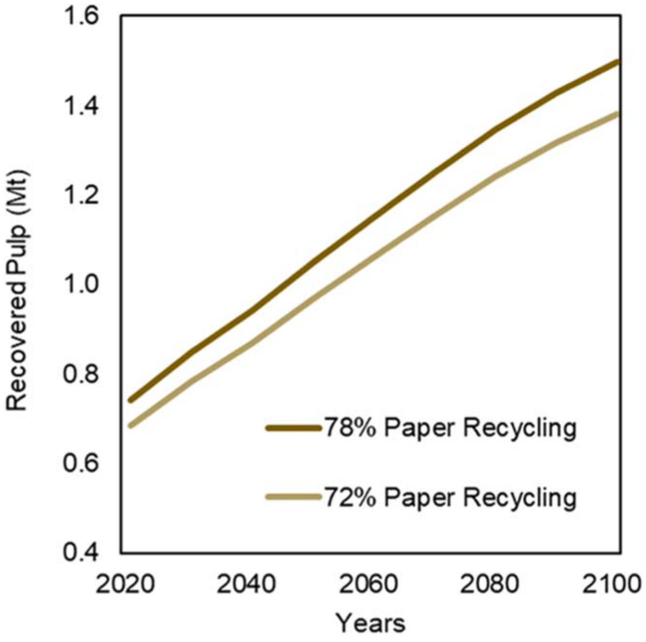

Figure 4. Recovered pulp quantity under the current paper recycling rate of 72% and under the target rate of 78% paper recycling. The saved pulp quantity equals the difference of the two lines and constitutes the starting point of the *Conservation and Substitution / Substitution* + scenario, respectively.

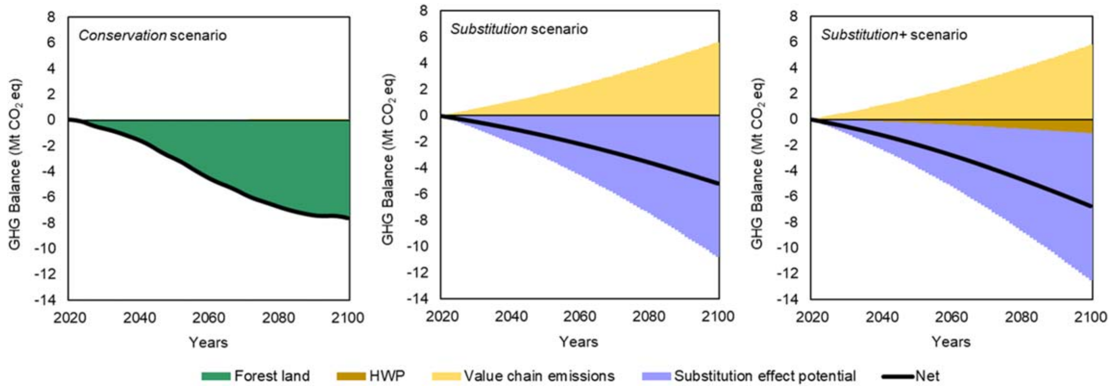

Figure 5. Cumulative GHG balances of the Conservation and Substitution/Substitution+ scenario making use of the "saved" primary pulp amount from the additional recovered pulp. Note: Negative values indicate reduced GHG emissions.

thus given when aiming for conserving forests in form of saving the additional efficiency gain by omitting pulplog harvest.

The *Conservation* scenario has an additional cumulative mitigation of −0.7 Mt CO_2 eq within the first 10 years from 2020–2030. The additional biogenic forest carbon almost exclusively contributes to this outcome with 99% as a consequence of the decreased pulplog harvest whilst fossil emissions from the additional paper recycling activity or saved forest operations are negligible with the remaining 1% contribution. In the long term, i.e., from 2020–2100, this cumulative mitigation is increased to −7.6 Mt CO_2 eq. The *Conservation* scenario could thus contribute to Sweden's required additional biogenic carbon sink under the EU LULUCF regulation. Here the requirements for Sweden are the highest among all EU member states and call for an increase of −4.7 Mt CO_2 until 2030 (EC 2021c, 2021a). The *Conservation* scenario could thus add to about 15% to reach the EU LULUCF 2030 target for Sweden.

However, this outcome of the *Conservation* scenario is connected to uncertainty factors. The first is the omission of detrimental climate change related effects such as forest disturbances, likewise beneficial effects, such as CO_2 fertilization. As mentioned previously, these were omitted due to insufficient ability of the forest modelling tool Heureka PlanWise to simulate these effects appropriately (Mazziotta *et al* 2022). This poses a great need for improving forest-based system's analysis, not only for the purpose of assessing climate effects. The second uncertainty factor is the location where the pulplog harvest savings would occur across Sweden. Within the same time frame would saving pulplog harvest, e.g. via reduced thinnings, in southern Sweden induce a larger carbon sink effect, than in northern Sweden, foremost due to the latitudinal climate and forest growth gradient (Skytt *et al* 2021). However, since negative impacts on forests from climate change such as forest fires and bark beetle risks have a similar spatial occurrence, these could offset this gain. A third uncertainty factor, here outside the system boundaries, is international forest carbon leakage. Commonly, leakage can largely outweigh additional forest carbon sinks in the region or country where decreased harvests occur (Lundmark 2022). However, in this study international forest carbon leakage can be neglected since the provision of Swedish wood products was not reduced, and thus no other harvest had to compensate elsewhere. Finally, a lower demand for pulpwood may not in any case lead to a decreased harvest rate. Pulpwood harvest quantities, as well as recovered paper quantities, are influenced by market dynamics, so that pulpwood may still be harvested but used, e.g., for energy generation. Inclusion of these market dynamics was however not part of this study.

The *Substitution* scenario yields a short-term cumulative climate change mitigation of -0.5 Mt CO_2 eq between 2020–2030. In the long-term, this increased to -5.0 Mt CO_2 eq between 2020–2100. This outcome arises from the potential substitution effect of replacing cotton fiber contributing to 66% of the total climate impact, which is larger than the fossil value chain emissions of additional paper recycling, dissolving pulp making, international transport, and viscose fiber production taken together, which add to the remaining 34% contribution. The *Substitution+* scenario excels over the *Substitution* scenario with yet additional 18% climate change mitigation during 2020–2030 (-0.6 Mt CO_2 eq), and 23% during 2020–2100 (-6.7 Mt CO_2 eq). Here the additional substitution effect potential including that from by-products contributes cumulatively to 63% of the GHG balance, and added biogenic carbon storage from the lignin-based concrete admixture to 6%, while the remaining 32% contribution arise from the fossil value chain emissions. Comparing these results to other national assessments analyzing additional climate change mitigation from increased paper recycling is difficult, first due to a lack of equivalent studies, and varying definitions of reference situations or system boundaries of somewhat comparable studies (Bais-Moleman *et al* 2018, Lorang *et al* 2022). However, one benchmark to the short-term cumulative mitigation of -0.5 Mt CO_2 eq found for the *Substitution* scenario between 2020–2030 can be the national fossil GHG emissions of Sweden during the equivalent past time frame 2010–2020 amounting to 54.2 Mt CO_2 eq (SCB 2024).

The three central assumptions that influence the outcome of the *Substitution*/*Substitution+* scenario are firstly the conversion ratio from recovered pulp, over pulplogs to the MMCF viscose, secondly the degree of the potential substitution effect, and thirdly, which products are replaced. In this study a mass ratio of one ton viscose per 5.3 tons pulpwood was given, while elsewhere more efficient ratios of approximately 2.5 tons of oven-dry wood are stated to be required for producing one ton of cellulosic fiber (Hassegawa *et al* 2022). This difference can underline the large variability which is present across production facilities along MMCF value chains considering their climate impact (Lidtfeldt *et al* 2022). As to the degree of the potential substitution effects, a perfect substitution, i.e., a replacement ratio of 1:1, was assumed between (i) recovered pulp and primary pulp, and (ii) viscose fiber and cotton fiber, respectively. Lorang *et al* (2022) highlight that whether increasing recovered pulp production yields climate change mitigation depends on whether perfect substitution or complementarity — i.e., only partial substitution and partial complementation of GHG emissions — is assumed. Indeed, complementarity in the form of overproduction is common in the apparel sector. Globally it is assumed that 10%–40% of all garments produced yearly, i.e., 15,000–45,000 Mt, are never sold or worn, but landfilled, or destroyed elsewise (WGSN 2023). This underlines that overproduction is not only commercially ineffective, but greatly compromises the garments industry's sustainability, or climate agenda. Future research should therefore add to the current understanding of complementarity or substitutability between wood-based and non-wood based products, e.g. via econometric analysis (Hurmekoski 2024). Meanwhile, assuming alternative products from pulpwood than MMCF, such as wood panels, or bioenergy would have led to different outcomes of the *Substitution*/*Substitution+* scenario. However, this could have implied a lower climate change mitigation since out of a large bandwidth the wood use for textile application was shown to yield the highest substitution effect on the product level (Leskinen *et al* 2018).

Fossil GHG emissions along forest value chains in Sweden must reduce substantially to align with Sweden's target of reaching carbon neutrality by 2045 (Government Offices of Sweden, Ministry for the Environment 2020). Global decarbonization requirements also apply to the substitution effects, i.e., the potentially avoided fossil GHG emissions from global production of cotton fiber, petrol, or cement. Fossil GHG reductions or even fossil GHG phase-outs may however differ greatly depending on the geography of sourcing and production. Decarbonization requirements thus imply important dynamics in the fossil GHG balances of the *Substitution*/*Substitution+* scenario which were however not considered here due to their unknown development. Accordingly, caution is warranted as to the uncertainty connected to the fossil GHG balances presented in this study. In the desired state of fully achieving decarbonization across the industrial sectors involved in wood

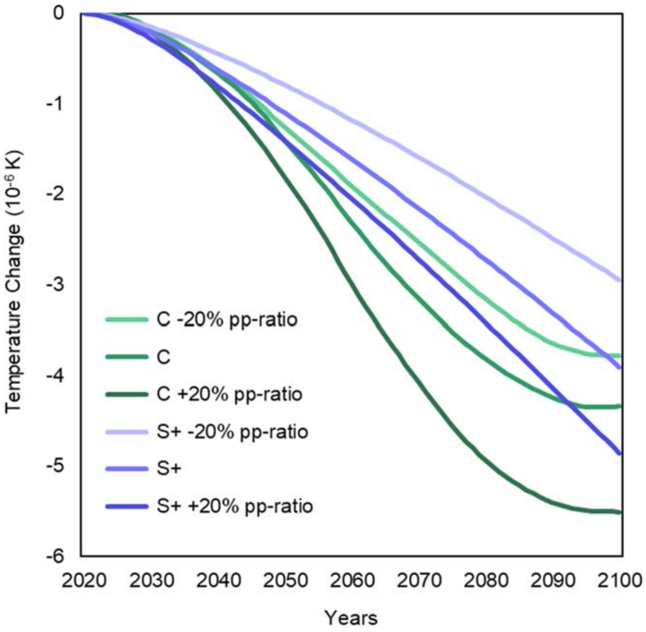

Figure 6. Atmospheric temperature change of the *Conservation and Substitution+* scenario including the sensitivity analysis in which the primary pulp to pulplog ratio (pp-ratio) is increased or decreased by 20%, respectively. This implies changed pulplog savings in the *Conservation* scenario and altered dissolving pulp and thus MMCF and by-product availability in the *Substitution+* scenario. Note: C = *Conservation scenario*, S+ = *Substitution+* scenario.

product systems (including those of the substituted products), the role of fossil GHG balances would fade and that of biogenic carbon increase.

3.2.2. The role of pulplog saving efficiency, by-products, and replacement ratio between MMCF and cotton fiber

Figure 6 displays the sensitivity of the results from the *Conservation* and *Substitution+* scenario depending on the pp-ratio, i.e., primary pulp to pulplog ratio. The pp-ratio alters the saved pulplog efficiency in the *Conservation* scenario, as well as , in the *Substitution+* scenario with consequential changes in the dissolving pulp, and thus MMCF availability.

Overall, changing the pp-ratio has moderate effects on the climate change mitigation of either scenario. A change of ±20% in the pp-ratio increases the climate cooling of the *Conservation* scenario by +28% or decreases it by −15%, while for the *Substitution+* scenario this effect amounts to +26% or −26%. However, irrespective of an improved primary pulp to pulplog ratio, and inclusion of the by-products' additional substitution effect and biogenic carbon storage, the overall inferior climate change mitigation compared to the *Conservation* scenario remains. Only if a decreased pulplog saving efficiency under the *Conservation* scenario and simultaneously an improved dissolving pulp and thus MMCF availability, as well as application of the by-products under the *Substitution+* scenario is given, would the *Conservation* scenario induce an inferior climate cooling. This outcome highlights that it requires joint improvements across the industry to generate a superior climate change mitigation from MMCF production than can be achieved by means of reduced pulplog harvest activity. Indeed, next to the use of by-products, several developments including industrial initiatives and pilot tests are globally underway investigating more sustainable and innovative production technologies of MMCF (Textile Exchange 2022). One approach is the use of recovered post-consumer textile fiber as a raw material for viscose production. This method has shown promising potential to reduce not only climate impacts (Paunonen *et al* 2019), but also the area of land use per unit of fiber (Hammar *et al* 2023). However, still in 2021 only a very small share of less than 1% of the global fiber market was based on recycled textiles (Textile Exchange 2022) so that fundamental developments are required towards a more sustainable textile industry based on recovered fiber.

In this study, the conservation of forests was found to lead to the largest climate change mitigation. This finding is further substantiated in the second sensitivity analysis (Figure 7) when a 1:0.8 replacement ratio between MMCF and cotton fiber is assumed in the *Substitution+* scenario. This highlights the implications as to the climate effects when only imperfect substitution between MMCF and cotton fiber is assumed which was found by recent econometric analysis (Hurmekoski 2024). In contrast, reaching comparable climate change mitigation as the *Conservation* scenario by MMCF substituting cotton fiber requires an ambitious replacement

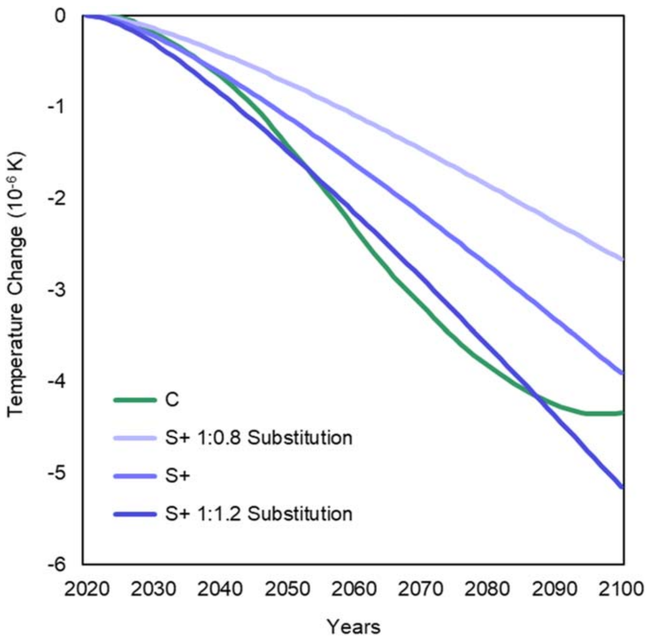

Figure 7. Atmospheric temperature change of the *Conservation and Substitution+* scenario including the sensitivity analysis in which the replacement ratio of MMCF for cotton fiber is changed by ±20%, respectively. This implies either partial complementarity among the two fiber types (1:0.8 replacement ratio), or improved substitution conditions (1:1.2 replacement ratio). Note: C = *Conservation scenario*, S+ = *Substitution+* scenario.

ratio of 1:1.2, which could highlight aforementioned need for concerted substantial production efficiency increases, property improvements, or demand changes for MMCF.

Regardless of the type of additional fiber produced for textile making, a more moderate consumption within a sufficiency-driven business model could thus further enhance the contribution to a more sustainable textile industry (Garcia-Ortega *et al* 2023) and combat the abovementioned overproduction in the apparel sector. The assumed additional MMCF fiber being generated in the *Substitution*/*Substitution+* scenario is based on an improved circular economy principle, i.e., through increased paper recycling, within a growth-oriented economy, thus aligning well with and endorsing business-as-usual production practices. However, efficiency gains as presented in this study risk facilitating rebound effects which may compromise the environmental gains achieved (Bocken and Short 2016) and thus seriously limit sustainability. A sufficiency-driven business model - instead of a growth-oriented—rather seeks to curb general resource consumption by reducing demand via education and consumer engagement and focuses on satisfying 'needs' instead of promoting 'wants' (Bocken and Short 2016) thereby offering potential to avoid ineffective overproduction. Extended lifetimes of already existing textiles through, e.g., improved fiber quality and garment making, or reuse of the textile for another purpose can be measures to not only reduce carbon emissions, but at the same time also water consumption and waste generation.

Indeed, next to the climate effects studied here water consumption is a crucial environmental impact category typically included in assessments studying textile systems. The *Substitution*/*Substitution+* scenario could, although inferior as to climate change mitigation compared to the *Conservation* scenario, therefore, bear an additional water saving potential given that the saved water consumption of cotton production outweighs the one of dissolving pulp production and viscose making (Shen *et al* 2010). Quantification thereof was, however, no aim of this study. On the contrary does the *Conservation* scenario bear additional environmental benefits such as those related to an enhanced biodiversity in Swedish forests due to decreased pulpwood harvest (Mazziotta *et al* 2022) for which indicators such as the area of old forest (gammal skog), tree species mixtures, or dead wood quantity per forest area could be considered (Jonsson *et al* 2019). Detrimental consequences from indirect land use change, on the contrary, could be abated following the *Substitution*/*Substitution+* scenario, as cotton cultivation can displace cultivation of other crops to other geographies. Given the assumption of a real substitution of cotton fiber by MMCF, and an average cotton yield of around 3.2 t ha^{-1} $year^{-1}$ (FAO 2023), the additional viscose supply could imply saving agricultural land of about 64,000 ha dedicated for cotton cultivation, which could be used elsewise. Consequently, a distinct trade-off between environmental impacts exists for the two general options studied here for how additional paper recycling in Sweden can mitigate climate change, which must be considered when evaluating the sustainability of each of them.

4. Conclusions

There is considerable two-sided political pressure on the Swedish forests to increase the biogenic carbon sink through enhanced forest carbon sequestration while at the same time cater for a continuously growing demand for wood-based products. This suggests that increased circularity could be a way to alleviate this pressure. With that background, this study explores how increased paper recycling in Sweden could best be used to mitigate climate change. More specifically, we analyse whether conserving forests or exploiting substitution effect potentials results in superior climate change mitigation from an increase in paper recycling, given that the resulting additional supply in recovered pulp replaces primary pulp. Two overall scenarios are put forward. The first - *Conservation* scenario - keeps the supply of pulp products constant and uses the exempt primary pulp quantity to reduce pulplog harvests in Swedish forests. The second - *Substitution* scenario - makes use of the freed up pulplogs (with unchanged fellings) to produce MMCF from dissolving pulp in order to exploit potential substitution effects by replacing cotton fiber. A sub-scenario, *Substitution+*, furthermore accounts for the role of by-products from dissolving pulp making.

The results suggest that the largest climate change mitigation effect can be achieved if an increase in Swedish paper recycling is used to reduce pulplog harvests and enhance the forest carbon sink, rather than producing additional pulp-based MMCF with unchanged pulplog harvests. Increasing the paper recycling rate in Sweden could thus be used to decrease the harvest pressure on national forests and simultaneously contribute to the country's LULUCF-target for 2030. This conclusion is reinforced when assuming imperfect substitution among MMCF and cotton fiber, but also considering the substitution effect potential from by-products of the dissolving pulp making, together with an improved dissolving pulp availability. At last, climate change mitigation from reduced Swedish pulplog harvests thanks to increased paper recycling in Sweden would furthermore align well with a more efficient and sufficiency-based textile business relying on constant textile supply levels.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that the mutual funding by Swedish University of Agricultural Sciences and Stora Enso Oy may be considered as a potential competing interest.

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