The forest carbon debt illusion

Contrary to common views, harvesting from managed forests does not delay climate benefits

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Summary

- The construct of a carbon debt / payback time accruing from harvesting of wood from forests is firmly rooted in climate science, the public forest debate as well as in EU-level policy processes related to forest management strategies.
- The forest carbon debt and payback time concepts were reviewed and applied to the actual case of Swedish forests, forestry and forest-based industry for the period 1980-2019 using official and precise statistics. This 40-year historical period is valid also for illustrating expected developments and management options in coming decades;
- Results confirm that no carbon debt or payback time accrue from harvesting operations in Swedish forestry. On the contrary a carbon asset is continuously built up in the forest, in parallel with harvesting of biomass for climate-smart products;
- The total and actual positive climate effect of the Swedish forest-based sector was -3.5 Gt CO_2e for the period 1980-2019, equivalent to c. -80 Mt CO_2e/yr, more than compensating for territorial fossil emissions reported by Sweden for the same period;
- No climate advantage was found for no-harvest or reduced-harvest scenarios, despite commonly expressed views in the debate. On the contrary each alternative scenario resulted in higher levels of atmospheric carbon both with 10-year and 40-year horizons;
    - The two no-harvest scenarios performed worse than the as-actually-managed scenario at -2.4 and -1.6 Gt CO_2e respectively and would also each have caused 1.4 Gt CO_2e of additional fossil emissions compared with the as-actually-managed scenario. By comparison, the Swedish overall territorial fossil emissions were 2.1 Gt CO_2e for the same period;
    - The reduced-harvest scenario (10% reduction of harvests) overall performed as the as-actually managed scenario, but with 0,15 Gt CO_2e additional fossil emissions over the period (4 Mt CO_2e/yr);
- One major and additional consequence of the no-harvest and reduced-harvest scenarios relative to the as-actually-managed scenario is that stable fossil carbon deposits are withdrawn and used, while storage in forest living biomass is left unused and thereby increase. This can be seen as shifting stable fossil deposits to more volatile storage in living biomass. Aside of direct climate impact of the scenarios, storage in living biomass is obviously less stable than continued storage underground;
- Severe external effects on sustainable development were identified for both no-harvest and reduced-harvest scenarios in the form of lost jobs, negative impact on rural development, lost export revenues and large capital losses in forest land and forest industry. Possible relative impacts on biodiversity potentials and performance of climate change adaptation were also noted;
- Based on the findings, there is no support for the proposition to reduce or eliminate harvests from Swedish forests as a climate action;
- Contrary, the very large climate benefits that accrue from actively managed forests and manufactured products from the timber harvest are essential for achieving the required rapid reductions of fossil emissions as well as contributions to sustainable development;
- It appears as current public debate as well as EU-level policy development related to forest management is not well informed and that climate science needs to revisit the forest carbon debt construct.

Background - What is the issue?

The urgency argument – putting time pressure on climate action

The Intergovernmental Panel on Climate Change (IPCC) provides an authoritative knowledge base on human-caused climate change, including scenarios that model consequences under different assumptions on future emission pathways. IPCCs assessments laid a foundation for the Paris Agreement (UN, 2015) in which the world's governments agreed on the aim to limit anthropogenic global warming to

"..well below 2 ℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 ℃.."

Importantly, this global response is conditioned to be achieved

"*..in the context of sustainable development and efforts to eradicate poverty*".

Following the Paris Agreement, IPCC prepared a Special Report on limiting global warming to 1.5°C, the so-called SR15 report (IPCC, 2018), focusing on the most ambitious end of the Paris Agreement aim. The SR15 report includes updates of the scientific knowledge on climate change impacts, mitigation pathway options and socio-economic analyses. The focus for the current paper is Chapter 2: "*Mitigation pathways compatible with 1.5°C in the context of sustainable development"*. This is where a "remaining carbon budget" is calculated and timeframes related to this budget suggested.

Section 2.2.2 of the SR15 report estimates the remaining 1.5°C carbon budget. This is a complicated assessment of different scenarios and with high uncertainties. The section ends with the statement *"As a result, only medium confidence can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty."*. Nevertheless, the findings have been used to enable a robust debate on the required pace of emission reductions. The numbers say that as of 1 January 2018, there remained a budget of 580 Gt CO_2 for a 1.5°C target and 1,500 Gt CO_2 for a 2°C target (IPCC, 2018 p.108).

In the following sections of SR15 (2.3-2.6), further modelling is applied to determine the pace by which (net) emissions need to be reduced to stay within the stipulated budget and potential development scenarios to achieve this. As global emissions stand at about 40 Gt CO_2/year, it is clear that the calculated 1.5°C budget corresponds to between 10 and 20 years of current emissions and consequently introduces a sense of urgency for this monumental challenge. Among many assumptions, the scenarios include negative emissions from Carbon Capture and Storage (CCS) as well as displacement of fossils by increased use of bioenergy and bio-based materials.

The time pressure established by the IPCC SR15 report has been widely used in the policy discourse and debate. One line of thought has been to distribute the remaining carbon budget by country so as to bring in a justice argument that poorer countries should carry less burden in the climate efforts (Alcaraz et al., 2018), which of course increases the urgency even more for richer countries.

Despite the considerable uncertainties stated by IPCC, the remaining carbon budget has been widely used in the debate as it is considered an easily understood measure that can help impact public opinion (Carbon Brief, 2020, 2018; Carbon Tracker, 2020; WRI, 2018). However, the concept has also been criticized as oversold and oversimplified (Harvey, 2018).

Climate activism has picked up the argument of remaining carbon budgets, for example Greta Thunberg in the Swedish Radio Summer Talk series in 2020 (Sveriges Radio, 2020), replicated in English on BBC, stating to a huge audience that only 7.5 years of current emissions remain, and that these include land use "*such as forestry and agriculture*".

What do forests have to do with it?

Forests are linked to climate policy in several significant ways. Since the UNFCCC Conference of the Parties (COP) in 2007, initiatives to reduce emissions from deforestation and forest degradation (REDD) have had a high profile as a conceived low-hanging fruit that could be realized in the relatively short term. Policies around Land Use, Land Use Change and Forestry (LULUCF) regulate reporting and commitments for signatories of the Kyoto Protocol, including all European Union member countries. These arrangements have in common that land-based sectors (mainly agriculture and forestry) are handled separately from other economic sectors with respect to climate reporting and policy. As a result, there is more focus on the sink (removals) of carbon into growing forests as well as the storage of carbon in forests, than on climate benefits of manufactured forest-based products.

In IPCCs global models, the harvesting of trees from forests is considered an anthropogenic activity that leads to carbon emissions, whereas the biological growth of trees is mainly considered in the results as a non-anthropogenic "natural response". As a result, the forestry sector becomes a source in IPCCs global models, emitting a full 11% of all anthropogenic greenhouse gas emissions. At the same time, the same models account for a considerable non-anthropogenic net sink in growing forests, resulting in an overall net sink in the world's forests (IPCC, 2019, p. 9). This structuring of climate analyses may have inspired proponents that argue for less forestry. Contrary to this methodology, the LULUCF reporting by countries are structured to assess the total carbon storage changes in forests, which results in major net sinks reported for Sweden (corresponding to c. 80% of territorial emissions) and EU member countries (corresponding to c. 10% of EU territorial emissions) (Figure 1). An important update to IPCCs global models is underway, supported by a new study that suggests how the differences between IPCCs models and national LULUCF reporting can be reconciliated (Grassi et al., 2021)

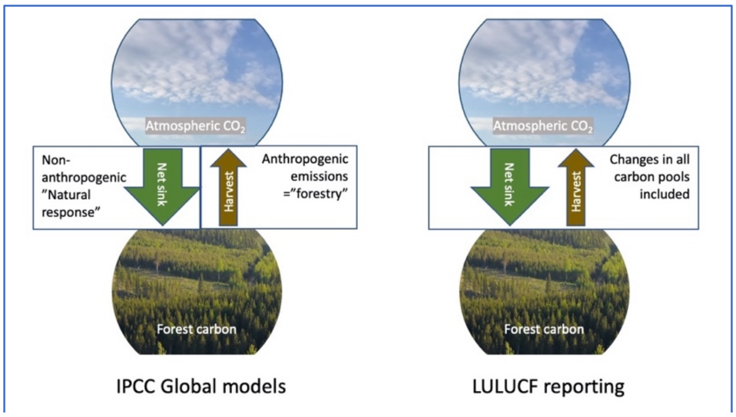


Figure 1. Principal difference between IPCC and LULUCF in representation of forestry carbon impact. The IPCC global models implicate forestry as part of the climate problem as forest management for improved growth and stability of living trees are not considered part of "forestry" (IPCC, 2019, p.9).

Such increasing storage of carbon in forests are considered an asset for climate policy as they offer a buffer for fossil emissions. So-called “net-zero” goals by countries, cities, regions and corporations include, in most cases, carbon offsets in forests to compensate for fossil emissions that are not eliminated at the required pace. In this way, increased carbon storage in forests is used politically to meet some of the urgency requirements in climate change mitigation (Carbon Disclosure Project, 2020; UNFCCC, 2020). While forest carbon storage may help in mitigation efforts, such “net-zero” and carbon offset approaches using forests have also been criticized as they don’t represent real emission reductions and because they may hinder other climate or development efforts (Song, 2019).

The urgency argument has also been applied as an argument against active forestry, i.e., harvesting of trees, even if the forest is managed for sustainable yield and harvesting remains below the overall forest growth. It is widely accepted that the forest carbon stock in such cases increases over time and the carbon budget thereby is positive. However, a reasoning is made that harvesting trees will cause emissions in the short term, while it will take a long time before that amount of carbon is reabsorbed in the forest. This would mean that a temporal “carbon debt” is accrued, which is not acceptable in light of the short-term requirement to bring down our carbon dioxide emissions. These biogenic emissions from a circular forest management system are, according to this reasoning, no different from fossil emissions of carbon dioxide as it will all end up in the atmosphere. For this reason, it is argued, forest harvest should be reduced or cancelled, so as to preserve the carbon storage in the forest.

The carbon debt concept

Carbon debt origins

Carbon debt was originally a concept used for illustrating how richer countries historically have caused large greenhouse gas emissions while building up their economic wealth. Conceptually this has created a “debt” to poorer countries that have caused much less emissions and also not enjoyed the same level of economic development. GHG emissions continue to be considered an unavoidable externality in achieving economic growth and at the same time these emissions must now be curbed at the global level. Consequently, the historical emissions in rich countries are considered an unfairness, or a “carbon debt”, to poorer countries that are expected to take part in the global reduction of emissions while at the same time aiming for economic growth of their own. How to compensate for this historical carbon debt has been a long-standing item in the political discourse around climate change.

Carbon debt when clearing land for biofuel crops

The concept was later applied in a different meaning to land clearing for biofuels (Fargione et al., 2008). The conversion of, e.g., forests to biofuel crop farming cause a significant one-off deforestation emission, which would take a long time to “pay off” with climate benefits as farmed biofuel displace (substitute) fossil fuels. Hence a “carbon debt” is incurred at the establishment of the biofuel farming. Conversion of tropical rainforests to palm oil plantations for biofuels was estimated to incur a carbon debt that would be take 86 years to “pay back”. On the other hand, conversion of abandoned farmland did not incur any carbon debt at all as no biomass was initially removed. In other words, the starting land condition and the level of reduction in carbon storage are what determine the carbon debt. The Fargione et al. (2008) approach has been applied in a number of studies that explore the carbon debt from similar land clearing perspectives, e.g. Achten and Verchot (2011); Searchinger et al. (2008). This line of research has often been used to argue against bioenergy/biofuels as a climate solution in the short or medium term.

Carbon debt in managed forests

The suggestion that using biomass from managed forests also incurs a carbon debt was first modeled by Holtsmark (2010) and Mitchell et al. (2012) for different forest management regimes. These papers have the limitation that no other use of harvested biomass than bioenergy is considered. In reality bioenergy is typically a by-product of solid wood and fibre products in the forest-based sector, so it does not drive decisions on forest management or harvesting.

Figure 1, copied from Mitchell et al. (2012), which builds on Equations 1 and 2, are central as they clarify that a carbon debt occurs when the initial carbon stock in the forest is reduced due to the biomass harvest. The figure also introduces a “carbon parity” point which is when the climate effect of the managed (harvested) forest catches up with the unmanaged (no-harvest) scenario as bioenergy displace (substitute) fossil energy, i.e a form of “break-even point” between the scenarios. In the debate, distinction between carbon debt and carbon parity is often confused (e.g. Aktuell Hållbarhet, 2020; TV4, 2020b). To reduce risk of misinterpretation, the findings of this report use “carbon debt” for illustrating the situation until the break-even point. That is, the concept “carbon parity” is not used.

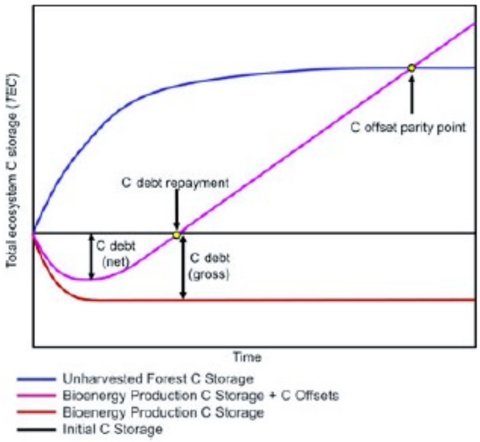


Fig. 1 Conceptual representation of C Debt Repayment vs. the C Sequestration Parity Point. C Debt (Gross) is the difference between the initial C Storage and the C storage of a stand (or landscape) managed for bioenergy production. C Debt (Net) is C Debt (Gross) + C substitutions resulting from bioenergy production.

$$(1)\quad \mathrm{C}^{\mathrm{m}}_{\mathrm{debt(t)}} = \mathrm{C}^{\mathrm{m}}_{\mathrm{storage(t)}} - \mathrm{C}^{\mathrm{m}}_{\mathrm{storage(0)}} - \sum_{\mathrm{t}=0}^{\mathrm{n}} \mathrm{C}^{\mathrm{m}}_{\mathrm{harvest(t)}} \times \eta_{\mathrm{biomass}}$$

$$(2)\quad \mathrm{C}^{\mathrm{m}}_{\mathrm{differential(t)}} = \mathrm{C}^{\mathrm{u}}_{\mathrm{storage(t)}} - \mathrm{C}^{\mathrm{m}}_{\mathrm{storage(t)}} - \sum_{\mathrm{t}=0}^{\mathrm{n}} \mathrm{C}^{\mathrm{m}}_{\mathrm{harvest(t)}} \times \eta_{\mathrm{biomass}}$$

Nabuurs et al. (2017) applied the carbon debt/parity model on European forests. They conclude that no carbon debt is incurred through European forest management as carbon storage in the forest continuously increases. This is because only part of the biomass growth in the forest is harvested. The study used modelling of forest developments and only considered harvest of biomass for bioenergy to determine parity points. They conclude that parity occurs only after 2080 or much later in some scenarios. This appears to be an argument for reducing harvests to maximize climate effect of forests at least within a time perspective of a few decades.

In 2017 a study by Chatham House criticized the EU policies on bioenergy, in particular the subsidies applied to import wood pellets to replace fossil coal in low-performing power generation facilities in the UK (Brack, 2017). The study also argued robustly that harvesting wood for biomass are negative for the climate due to lower energy efficiency compared to fossils and, specifically, that the payback time would cause an unacceptable delay in the expected climate benefits.

In early 2021 a comprehensive report on forest-based bioenergy was published by the European Commission (EC Joint Research Centre, 2021) as input to the ongoing political process leading towards a new EU directive on renewable energy. The report makes considerable use of the carbon parity/payback time concept, illustrated in a simplified manner shown in Figure 2. While the report aims to provide comprehensive inputs for Europe-wide political decisions, it does at the same time discount its own findings on payback times as valid only on a limited scale: "*…these results should be interpreted as representing mainly the impact of the production of a relatively small quantity of the product (e.g. 1 MJ) and not representing the impacts of a large-scale deployment of bioenergy which would then affect installed production capacities and lead to many of the market-mediated effects mentioned above."* (EC Joint Research Centre, 2021, p.100). Still, the report bases its main conclusions on a categorization of payback times for a range of bioenergy systems across the continent, which appears then not to comply with the state of knowledge or models at hand.

The conclusions of above referred studies were drawn from approximate models, partly predicting a distant future, and with system boundaries that mainly narrowly considered forest biomass for bioenergy and generally did not consider externalities beyond energy supply and climate change concerns.

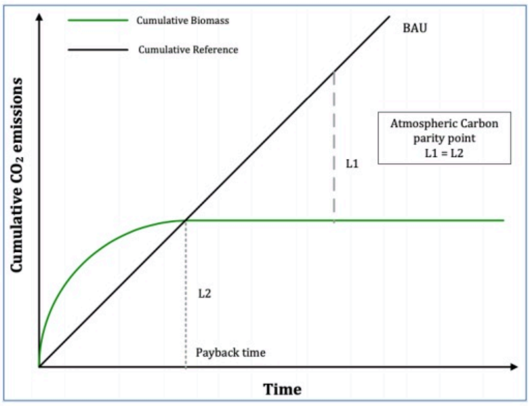


Figure 34. Visual description of payback time and atmospheric carbon parity point. Green Line: drop in the forest carbon stock due to bioenergy production; Black line: accumulated reduction in carbon emissions from substitution of fossil fuels. Source: *(Agostini et al, 2014)*

Figure 2. Simplified application of carbon parity/payback time model (from EC Joint Research Centre (2021), p. 101)

Literature review

As part of the current analysis, a literature review was carried out to illustrate research findings relevant to the forest carbon debt topic. In total, 44 articles and reports were included. Of these, 11 were classified as synthesis papers and 31 as original modelling or case studies as summarized in Annex 1.

Research on the forest carbon debt topic appears largely to have evolved from the bioenergy crop analysis approach by Fargione et al. (2008). The synthesis papers were published in the period 2013 to 2021 and provide quite disparate conclusions. Miner et al. (2014) makes a positive conclusion on the long-term climate contributions of sustainably managed forests and products derived from them. Chatham House (2017); EC Joint Research Centre (2021, 2014); Giuntoli et al. (2020); Norton et al. (2019); Ter-Mikaelian et al. (2015); Vanhala et al. (2013) provide an opposite view of large carbon debt problems from wood harvests in the short to medium term. At the same time, Bentsen (2017), Helin et al. (2013) and Lamers and Junginger (2013) suggest that conclusions are entirely dependent on prevailing variations in assumptions and scenario model constructions, which in turn suggests that the policy debate is not well informed.

Of the reviewed modelling/case studies, 23 relate to continuous forest management. Of these, almost all state that a carbon debt accrues at harvest, based on long-term scenario models using assumptions of forest developments rather than real-world data. In a number of studies, the scale is confined to the individual stand. Most exclude economic externalities from the analysis. Most studies are also fixed on bioenergy as the only studied product from the forest (Table 1, Annex 1).

Drawing from the synthesis studies and the reviewed approaches of the modelling/case studies, it appears as the knowledge base is not well developed, highly dependent on assumptions and model constructions, and with limited cross-reference with real-world forest management (Goodwin et al., n.d.; Madsen and Bentsen, 2018).

Table 1. Overview of scope and conclusions from reviewed literature (23 studies) related to carbon debt in managed forests, see also Annex 1

Main scale studied	**n**	**n studies stating that a carbon debt accrues at harvest**			**n studies that**		
		yes	**depends**	**no**	**apply long-term scenario models w extrapolation to determine results**	**do not address economic externalities**	**only consider bioenergy as output (no other products)**
Stand	6	5	1	0	6	5	4
Landscape	11	9	1	1	9	7	8
Sector	6	5	0	1	6	4	3
Total	**23**	**19**	**2**	**2**	**21**	**16**	**15**

Forest carbon debt in current debate / discourse

The forest carbon debt argument is frequently used in current debate on how forests and forestry can best contribute to climate change efforts. It is often linked to the principle that bioenergy is considered climate-neutral in policy as well as climate reporting. Two distinct milestones for this debate was the 2008 World Food Security conference (FAO, 2008) and the EU Renewable Energy Directive (*Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*, 2009). The 2008 food conference was primarily oriented around the spike in food prices at the time, which included the induced fear that increased biofuel production would lead to permanently higher prices. This isolated theory has since been debunked as the price hike was attributed to a multitude of factors (HLPE, 2011).

The EU RED directive of 2009 was favorable of bioenergy and led to considerable subsidies for the purpose. This, in turn, triggered a lot of prominent dispute over the benefits of bioenergy, especially if sourced from forests. Notions of "dirtier-than coal" and "environmental lunacy" have been made by leading institutions and media (Chatham House, 2017; The Economist, 2013) together with campaign NGOs (Fern, 2020; RSPB, 2013; WRI, 2015) and academic platforms (Beddington et al., 2018; EASAC, 2018; Norton et al., 2019).

The debate continues to be strong in European media (BBC, 2017; Ends Waste and Bioenergy, 2017; The Guardian, 2019) and even more so in Swedish media where both researchers and other opinion makers make strong statements that forests should be left standing for the benefit of the climate, often coupled with perceived co-benefits for biodiversity (Aktuell Hållbarhet, 2020; Alestig, 2020; Dagens Industri, 2020; Dagens Nyheter, 2017; Greenpeace and Protect the forest Sweden, 2021; Nyhetsmagasinet Syre, 2020; Skydda Skogen, 2020; Svenska Dagbladet, 2018; Sveriges Radio, 2020; Sveriges Television, 2020; Transportnytt, 2020; TV4, 2020b, 2020a). A common denominator is the presumption that a carbon debt is incurred with payback times in the range of 50-100 years and that the urgency of the climate challenge does not allow for this delay.

In 2018 a joint conference between three Royal Academies in Sweden, KSLA, IVA and KVA, was held with the title *"Forests and the climate – manage for maximum wood production or leave the forest as a carbon sink?"* (The Royal Swedish Academy of Agriculture and Forestry, 2018). The title and scope of the conference made it very clear that the option of abandoning the forest as a climate action was seriously considered also in this broad academic setting.

In early February 2021, the largest Swedish daily newspaper suggested, as part of a series of critical articles about Swedish forestry, that science is divided on how the climate is affected by active forest management (Dagens Nyheter, 2021). Still, all quoted statements claimed that there a carbon debt accrues when harvesting forest stands, which would only be repaid after 70-140 years.

It appears, therefore, as the construct of a carbon debt / payback time is firmly rooted in forest science, the public forest debate as well as in EU-level policy processes related to forest management strategies.

In the following, an analysis based on real-world data is made to test the validity of the carbon debt concept under Swedish forest management regimes

Material & Methods: Carbon debt model applied on Sweden 1980-2019 & 2020-2059

The literature on carbon debt is generally based on modelled responses of the ecosystem under different harvest regimes. This gives a theoretical base for the concept but does not provide results that are calibrated to real-world situations. Consequently, results and conclusions are entirely dependent on assumptions and system boundaries implied by these assumptions. This in turn introduces a high risk of bias in the analysis, possibly influenced by circumstances and context of the research in question.

For this study, real-world data was used to establish a baseline scenario and to drive modelling of alternative scenarios. The Swedish National Forest Inventory (NFI) has delivered reliable official and detailed statistics on forest developments for almost 100 years (SLU, 2020a). Similarly, the Swedish Forest Agency has provided reliable, consistent official statistics on timber harvesting volumes since the 1950s (Skogsstyrelsen, 2018). Statistics were extracted for the period 1980-2019, summarized in Figure 3.

The forest status in 1980 comprises the starting point for scenarios below. In 1980, the standing stem volume was 2.3 bn m^3, corresponding to 3.1 Gt CO_2e living tree biomass. Over the 40-year period, the standing stem volume increased by almost 1 bn m^3, while during the same time period more than 3 bn m^3 were harvested (Figure 3).

Removals of branches for energy production are not included in the analyses – this represented about 5% of biomass removals in 2019.

The data represent all productive forest land in the country, c. 23.5 million hectares, including set-aside areas. This real-world development is referred to below as the "as-actually-managed" case which is the real-world result where about 80% of the area is managed for timber harvest and 20% as no-harvest (set-aside) areas. The total forest area in Sweden is 28 million hectares, but low-productive areas were not included as no harvests are considered there. From a climate perspective, however, also these areas constitute a net sink of atmospheric carbon (Naturvårdsverket, 2020; SLU, 2020a)

Looking to the future, national and official analyses of forest and harvest developments, a foundation for forest policy deliberations, predict a continuation of these historical trends. With continued active management, the growth, standing volume as well as harvesting levels will continue to increase at a similar pace over the coming decades. This is well investigated in official analyses, the latest labelled SKA15 (Skogsstyrelsen, 2015). Data from these projections were used to compare the historical developments 1980-2019 with an expected trajectory for 2020-2059.

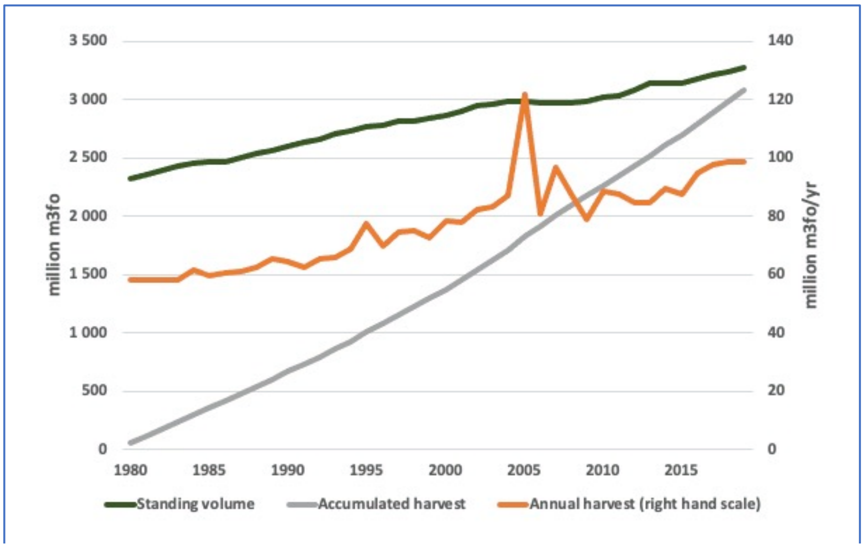


Figure 3. Developments of Swedish forest standing volume and timber harvest 1980-2019 based on official statistics

Scenarios, overview

Three scenarios were constructed to evaluate the carbon debt/parity developments:

- Scenario 0 – the as-actually-managed real-world development based entirely on official data;
- Scenario 1 – no-harvest scenario to replicate the carbon debt scenario by Mitchell et al. (2012)- Two sub-scenarios were developed, applying different parameters for future forest development under no-harvest;
- Scenario 2 – a reduced-harvest scenario where, in addition to already set-aside areas, overall removals were reduced by 10% as a more realistic alternative scenario, and also in line with some views expressed in the debate.

For all scenarios, standing timber volume numbers were converted to total living tree biomass following standard methodology in Swedish National Inventory Reports to UNFCCC (Naturvårdsverket, 2020). For scenarios 1 and 2 additional growth and natural losses in the forest were modeled based on the official baseline data. Scenarios 1 and 2 were compared with the baseline scenario 0 with respect to carbon debt, carbon parity, forest carbon storage, harvested wood product carbon storage, fossil displacement effect (substitution) and differences in fossil emissions. The soil carbon sink was assumed to be similar across scenarios and excluded from the analysis, even though reduced growth in scenario 1 would also lead to significantly reduced sink of soil carbon.

No variations between scenarios in overall human consumption levels were included. Such analysis would add considerable complexity and would have to include relative consumption increases/decreases of fossil-based products and energy compared with wood-based ones.

For scenarios 0 and 2 displacement of fossil emissions (substitution effect) was considered for the full mix of product categories, i.e. not only harvest for bioenergy as in Mitchell et al.

(2012) and other earlier studies, but also for solid wood products and fibre products, representing normal wood utilization in Sweden where different parts of the tree is used for either of these product categories (Figure 4).

The forest industry value chain uses a significant portion of the harvested wood as its own main energy source – this bioenergy component is not included in the displacement factor used here.

In addition, the forest industry value chain causes some fossil emissions, which are small in comparison with the positive effects of net sink and fossil displacement. Nevertheless, these emissions should be taken into account as a means to achieve the fossil displacement of the forest products, as done in Holmgren (2019).

The net fossil displacement (substitution) factor was conservatively set to 0.5 fossil tCO_2e per m^3 of harvested biomass, which includes a deduction related to fossil emissions caused in the value chain at 0,05 tCO_2e/m^3. This corresponds to displacement effects for the integrated mix of solid wood products, fiber products and bioenergy applied in several studies (Holmgren and Kolar, 2019; Leskinen et al., 2018; Lundmark et al., 2014).

In addition to the greenhouse gas flows, a comparison of externality effects on other sustainable development parameters was made between the three scenarios.

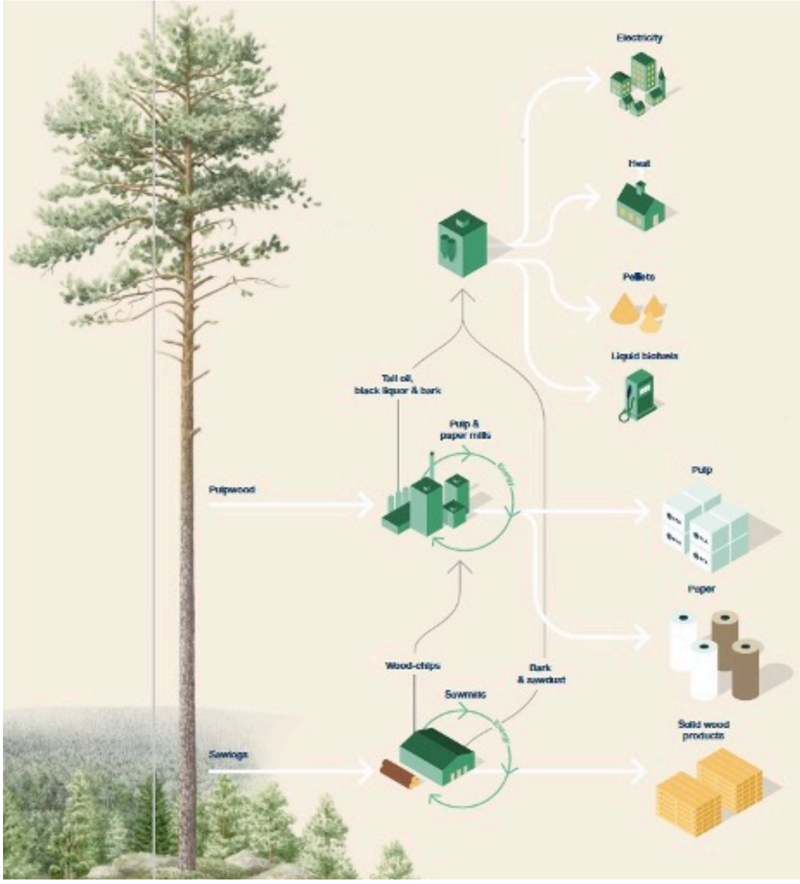


Figure 4. Illustration of how all stem biomass is used for a variety of products, in this study aggregated into (a) solid wood products, (b) fibre products, and (c) bioenergy. (Based on SCA Annual Report 2019, p.9)

Scenario 0: As-actually-managed (BAU)

This is the what-actually-happened scenario. No assumptions are required as to the forest development or harvests, which simply needs to be transformed into carbon flow and displacement equivalents.

The climate effect for the as-actually-managed scenario was calculated as:

$$(3)\ ClimateEffect = \sum_{t=1980}^{2019} LBsink_t + HWPstorage_t - StumpDecay_t + Displacement_t$$

where:

- $LBsink_t$ = net carbon sink (biological growth – natural losses – harvest removals) in living tree biomass in year t;
- $HWPstorage_t$ = change in Harvested Wood Products storage in year t
- $StumpDecay_t$ = emissions from decaying stumps, roots and branches in year t
- $Displacement_t$ = net displacement of fossil emissions by substitution in year t, taking into account fossil emissions made in the forest industry value chain

Net sink in Living Biomass was calculated directly from the statistics of forest standing volume as explained above.

Harvested Wood Products (solid wood and fibre/paper products) storage change was calculated as per methods applied in national reporting to the UNFCCC (Naturvårdsverket, 2020), to account for the delay of biogenic emissions from the harvested biomass that is used for solid wood or fibre products. The net increase of HWP storage increased from 4.6 Mt CO_2e/yr in 1980 to 6.6 Mt CO_2e/yr in 2019, reflecting officially reported levels for Sweden.

The slow and gradual decay of stumps, roots and branches left in the forest after harvest need to be incorporated in the model as this is an extended storage of carbon after harvest, similar to the effect of HWP. The non-stem components account for about one third of total living biomass (Naturvårdsverket, 2020) and was assumed to decay at a half-time rate of ten years, which is a somewhat higher pace than suggested by Melin et al. (2009).

Displacement effect set to 0.5 tCO_2e/m^3 harvested as explained above.

This scenario was also compared with a future 40-year scenario 2020-2059, based on SKA15, the latest comprehensive national and official investigation of future forest management strategies. It makes use of national forest inventory data and state-of-the-art growth and harvest models (Skogsstyrelsen, 2015). The scenario in SKA15 that best resembles the 1980-2019 as-actually-managed results appears to be the SKA15 “90% harvest” scenario. This is because historical harvests, as recorded, appears *de facto* not to have reached the predicted sustainable harvest potential. No assumption on efficiency gains, eg reduced fossil emissions per unit produced, were made for the future scenario.

Scenario 1a and 1b: No-harvest

The no-harvest scenarios would mean drastic changes to society, closing all forest industry and forest-based bioenergy production. It is assumed under this scenario that forest industry would not import harvested wood as this would represent a leakage in the analysis that may nullify other effects. The forgone forest-based products and energy is instead assumed to be replaced by corresponding fossil-based alternatives, meaning that the displacement effect in scenario 0 is reversed and represent increasing fossil emissions under the no-harvest scenarios.

The climate effect for the no-harvest scenarios (1a and 1b) were calculated as:

$$(4)\ ClimateEffect = ConversionEmissions + \sum_{t=1980}^{2019} LBsink_t - HWPstorage_t$$

where

- ConversionEmissions = Initial transformation emissions as a one-off transformation, representing major and required modifications to energy systems, infrastructure, industrial processing, building sector, manufacturing of consumer products and other economic activities towards fossil-based production if a no-harvest scenario were to be implemented. In addition, the export of wood and fibre-based products will likely to some extent be reversed to an import, likely adding considerable fossil emissions from less efficient value chains. These conversions were arbitrarily assumed to generate 100 Mt CO_2e of initial additional emissions that do not appear in the other scenarios, corresponding to two years of fossil emissions in Sweden. This is a *de facto* carbon debt situation, but in the opposite direction than normally applied, illustrating the major disruptions that scenarios 1a and 1b would cause.

- $LBsink_t$ = Net sink in living biomass in year t taking into account (a) additional growth on a higher volume of living biomass compared to scenario 0, (b) additional natural losses under no-management that reduce the net sink set to 4%/year for 1a and 6%/year for 1b (Table 2)

- $HWPstorage_t$ = change in Harvested Wood Products storage in year t, noting that these scenarios will lead to net emissions of HWPs that are phased out as there is no influx of new products to balance the storage loss. This effect is higher at the beginning of the period.

Table 2. Author-estimated additional natural losses under no-harvest scenarios from different causes and within a ten-year horizon. The no-harvest scenario implies very limited human interaction with and impact on the forest, which will rapidly increase natural losses. Total estimated additional losses of c. 5 Mm³/year correspond to 5% of growth. Based on this, two sub-scenarios (1a and 1b) were applied with assumed losses at 4%/yr and 6%/yr respectively. These additional losses should be considered conservative and could be much higher as a result of escalating insect populations or unpredictable fire regimes in unmanaged forests. By comparison, a baseline of actual annual natural losses in the BAU scenario is estimated at 14 million m³/year (SLU, 2020b), noting that a part of these losses are recovered through salvage logging.

Cause of additional natural losses under no-harvest	**Comment**	**Area affected**	**Sink loss**	**Storage loss**	**Total loss**	
		ha/year	**m3/ha/ye**	**m3 eqv/ha/yr**	**m3/yr**	**Mt CO2e/yr**
Windfalls	Sink loss from lost growth. Storage loss through early decomposition	10 000	6	50	560 000	0,7
Pests:						
Barkbeetles	Losses of more productive stands (spruce)	50 000	8		400 000	0,5
Wildlife	Probably no net effect					0,0
Wildfire	Loss of growth + storage (also soil losses)	20 000	5	200	4 100 000	5,1
No fertilizing		30 000	2		45 000	0,1
No planting	Later (and very large) effect	150 000				0,0
Reduced growth due to old age	No effect on 10 year horizon	200 000	0		0	0,0
Total					**5 105 000**	**6,4**

Scenario 2: Reduced-harvest

As presented above, arguments have been made that a partial reduction of harvest levels, e.g., by allowing stands to grow older would be a suitable climate action, helping in meeting estimated requirements of CO_2 reduction in the atmosphere in the next decade. A relatively modest and temporary reduction would also not impact the long-term sink potential in the forest in the way that a no-harvest scenario would, and it may have more acceptable external consequences. At the same time, risks of forest damages or calamities should not be ignored when mature stands are kept standing instead of being harvested, especially under changing climate conditions – a small risk factor has been included corresponding to a 30% higher level of natural losses compared with measured actual natural losses under BAU at 14 Mm^3/yr (SLU, 2020b). As for scenarios 1a and 1b it is assumed that the shortfall of harvested wood is not compensated by wood import, but instead leads to reduction in industry delivery with a corresponding reduced displacement effect and increased fossil emissions.

The climate effect for the reduced harvest scenario was calculated using Equation 3 with the following modifications to data input:

- Harvest levels were reduced by 10% with corresponding adjustments to HWP storage, Stump decay and Displacement of fossils
- Net sink in living biomass was adjusted to included additional growth on the slightly higher volume of living biomass compared with scenario 0, and additional natural losses as per above;

Results

Comparing 1980-2019 scenario outputs

Scenario outputs are summarized in Tables 3 and 4 and compared graphically in Figures 5, 6 and 7.

When using the carbon-debt model as established by Fargione et al. (2008), all scenarios result in significant positive climate effects. At the end of the 40-year period (1980-2019), the accumulated effect for the as-actually-managed scenario 0 is about -3.54 Gt CO_2e, or about -80 Mt CO_2e/yr. The no-harvest scenarios 1a and 1b indicate a smaller positive climate effects of -2.41 and -1.56 Gt CO_2e respectively, and the reduced-harvest scenario 2 results in a positive effect of -3.56 Gt CO_2e (Figure 5, Table 3).

There is no carbon debt accruing in the as-actually-managed scenario 0 (BAU) against any of the alternative scenarios. Further, there is no carbon parity point /payback time as the other scenarios consistently perform similarly or worse compared with BAU (Figure 5).

Scenarios 0 and 2 perform similarly throughout the 40-year. No-harvest scenarios 1a and 1b are consistently performing worse than the other scenarios (Figure 5).

Scenarios 1a and 1b result in considerable fossil emissions of 1.54 Gt CO_2e, or 1.38 Gt CO_2e more than the BAU scenario, which can be compared with the actual total GHG emissions of Sweden over the same period at 2.1 Gt CO_2e (World Bank, 2020). Scenario 2 result in accumulated additional fossil emissions of 0.13 Gt compared with scenario 0, or about 4 Mt CO_2e/yr, more than half the fossil emissions from the Swedish iron and steel industry (Naturvårdsverket, 2020).

Another way to illustrate the results is the carbon stock changes for each scenario, which is more closely related to official climate reporting where the concept of fossil displacement is not used. Focus is instead on changes in carbon pools, including the atmospheric carbon pool. For scenario 0 carbon stocks increase in living biomass, Harvested Wood Products, and decomposing stumps, roots and branches – counteracted by smaller fossil emissions - resulting in a net reduction of atmospheric carbon at -1,84 Gt CO_2e over the 40-year period. By comparison, scenarios 1a and 1b also lead to increases of living biomass, but these are counteracted by fossil emissions to a much higher degree, as well as a major loss of carbon stock in HWP. Consequently, scenario 1a results in atmospheric reductions of -0,87 Gt CO_2e thanks to a doubling of the living biomass stock, whereas scenario 1b results in practically no change at all for atmospheric carbon. Scenario 2 leads to slightly higher living biomass storage compared with Scenario 0, counteracted by higher withdrawals from fossil deposits for a total effect of -1,88 Gt CO_2e of atmospheric carbon. (Table 3, Figure 6, 7).

Given the focus on emission pathways in the coming decade, it is relevant to also illustrate performance of each scenario over the initial 10-year period (Table 4). On this shorter time horizon, scenario 0 performs best. Also, similarly, scenarios 1a and 1b lead to considerably higher fossil emissions at 0,30 Gt CO_2e, or 30 Mt CO_2e/yr, in the first ten-year period.

One major consequence of the no-harvest and reduced-harvest scenarios relative to the as-actually-managed scenario is that fossil carbon deposits are withdrawn and used, while storage in forest living biomass is left unused and thereby increase. This can be seen as shifting fossil deposit storage to storage in living biomass. Aside of calculated climate impact of the scenarios, carbon storage in living biomass is obviously less reliable than continued storage underground. Policy implications of such increased risks are however not further considered in this analysis.

Table 3. Comparison of scenario results for entire 40-year period 1980-2019

Scenario	Total climate effect 1980-2019[1]				Fossil emissions 1980-2019	Living biomass			Change in atmospheric carbon pool 1980-2019
	Biosphere carbon storage	Net fossil displacement[2]	(of which fossil emissions)[2]	Total		in 2019	increase since 1980		
	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	%	Gt CO_2e
As-actually-managed	-2,00	-1,54	0,16	-3,54	0,16	4,50	1,38	44	-1,84
No-harvest a	-2,41	-	(n.appl.)	-2,41	1,54	5,98	2,85	91	-0,87
No-harvest b	-1,56	-	(n. appl.)	-1,56	1,54	5,13	2,00	64	-0,02
10% Reduced-harvest	-2,17	-1,39	0,14	-3,56	0,29	4,83	1,70	54	-1,88

1) As per model proposed by Fargione et al. (2008). Negative numbers indicate (net) sink/displacement

2) Net fossil displacement includes deduction of fossil emissions in the value chain. Fossil emissions are also listed separately in the table.

Table 4. Comparison of scenario results for initial 10-year period 1980-1989

Scenario	Total climate effect 1980-1989[1]				Fossil emissions 1980-1989	Living biomass			Change in atmospheric carbon pool 1980-1989
	Biosphere carbon storage	Net fossil displacement[2]	(of which fossil emissions)[2]	Total		in 1989	increase since 1980		
	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	Gt CO_2e	%	Gt CO_2e
As-actually-managed	-0,59	-0,30	0,04	-0,89	0,04	3,52	0,39	13	-0,55
No-harvest a	-0,74	-	(n.appl.)	-0,74	0,30	4,02	0,90	29	-0,44
No-harvest b	-0,64	-	(n. appl.)	-0,64	0,30	3,92	0,80	25	-0,34
10% Reduced-harvest	-0,59	-0,27	0,04	-0,86	0,07	3,56	0,43	14	-0,52

1) As per model proposed by Fargione et al. (2008). Negative numbers indicate (net) sink/displacement

2) Net fossil displacement includes deduction of fossil emissions in the value chain. Fossil emissions are also listed separately in the table.

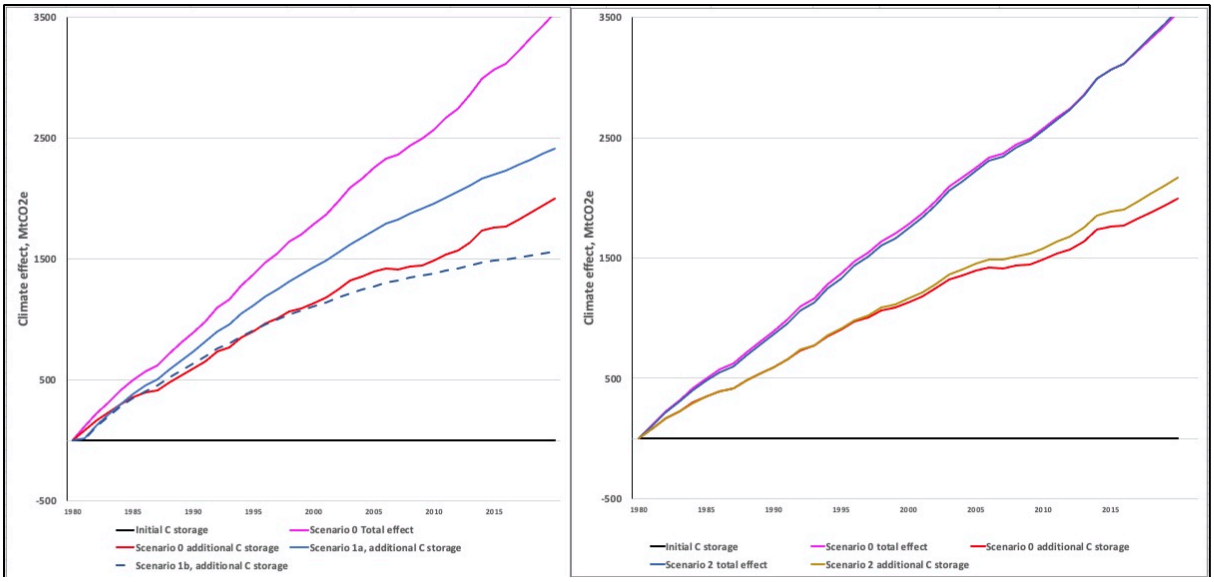
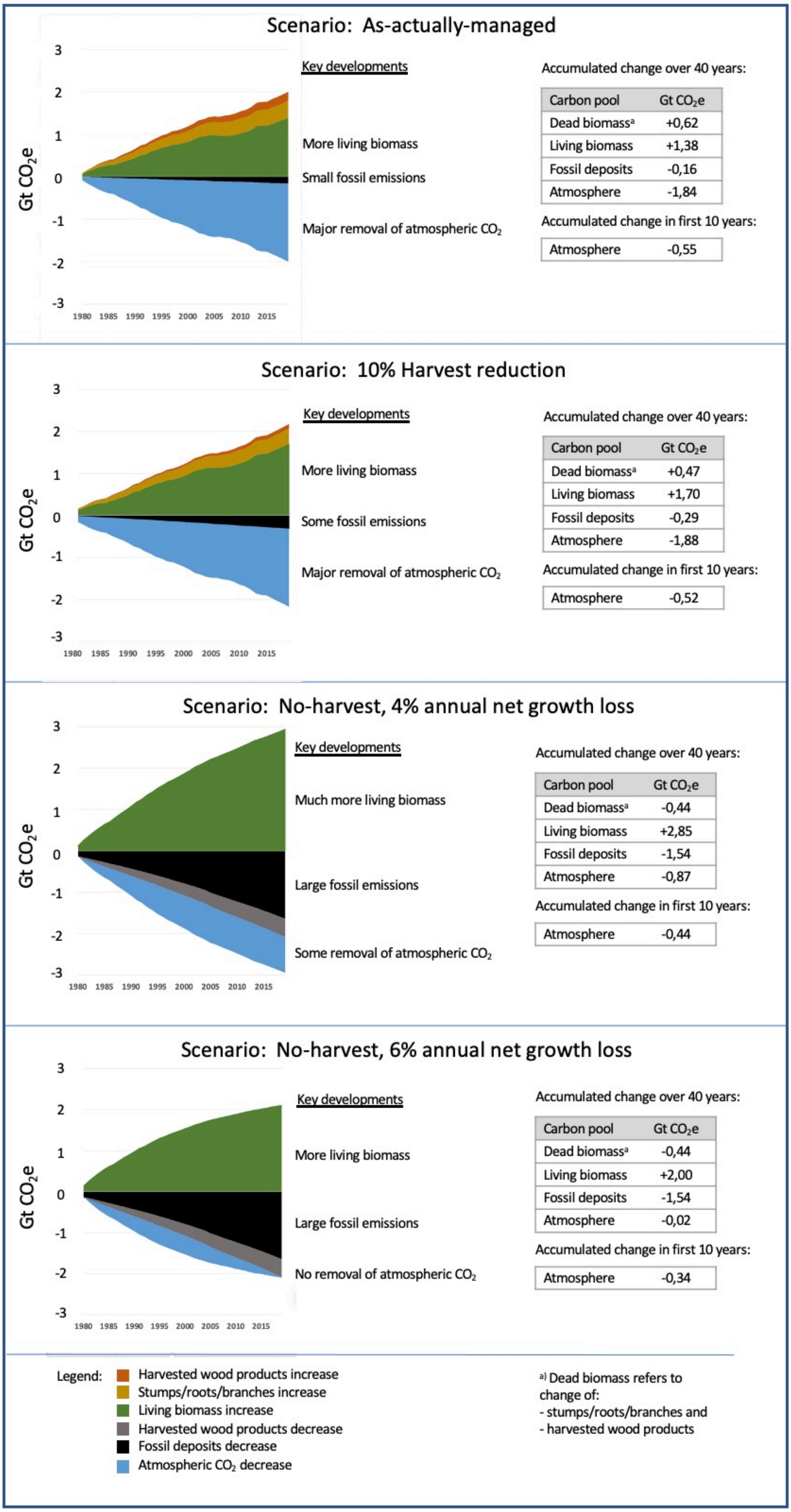


Figure 5. Carbon debt/parity model of (Fargione et al., 2008) applied to actual data for Sweden 1980-2019 for scenarios described in the main text and covering all productive forest land (23.5 Mha). All scenarios result in significant positive climate effects for the studied period. Left hand graph compares scenario 0 (as-actually-managed) with scenarios 1a and 1b (no-harvest scenarios with different levels of increased natural losses), Right hand graph compares scenario 0 (as-actually-managed) with scenario 2 (10% reduced harvest). No carbon debt or payback time appears for the as-actually-managed scenario. No-harvest scenarios perform worst, in addition to causing higher fossil emissions

Figure 6.

Accumulation of carbon storage changes for the four scenarios 1980-2019. All scenarios indicate increasing living biomass over time. The no-harvest scenarios lead to very high fossil emissions due to forgone displacement effects, and also losses of carbon storage in harvested wood products. The as-actually-managed and reduced-harvest scenarios provide most reduction of atmospheric carbon both in the short term (10 years) and the long term (40 years). The effects are of a very high magnitude with atmospheric removal in the range 1,8-1,9 Gt CO₂ over 40 years for the top two scenarios. As a reference, the accumulated fossil emissions for Sweden were 2,1 Gt CO₂e for the same 40-year period.



Accumulated change over 40 years:

Carbon pool	Gt CO₂e
Dead biomass[a]	+0,62
Living biomass	+1,38
Fossil deposits	-0,16
Atmosphere	-1,84

Accumulated change in first 10 years:

Atmosphere	-0,55

Accumulated change over 40 years:

Carbon pool	Gt CO₂e
Dead biomass[a]	+0,47
Living biomass	+1,70
Fossil deposits	-0,29
Atmosphere	-1,88

Accumulated change in first 10 years:

Atmosphere	-0,52

Accumulated change over 40 years:

Carbon pool	Gt CO₂e
Dead biomass[a]	-0,44
Living biomass	+2,85
Fossil deposits	-1,54
Atmosphere	-0,87

Accumulated change in first 10 years:

Atmosphere	-0,44

Accumulated change over 40 years:

Carbon pool	Gt CO₂e
Dead biomass[a]	-0,44
Living biomass	+2,00
Fossil deposits	-1,54
Atmosphere	-0,02

Accumulated change in first 10 years:

Atmosphere	-0,34

[a] Dead biomass refers to change of:
- stumps/roots/branches and
- harvested wood products

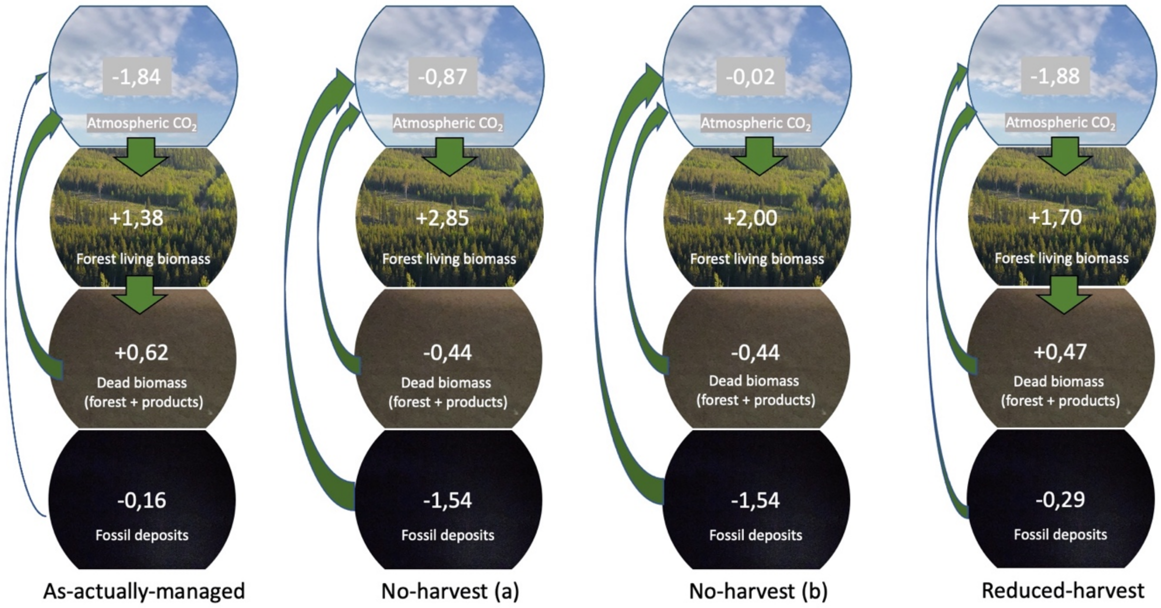


Figure 7. Accumulated impact (net effect) of each scenario for the 1980-2019 period expressed as changes in carbon storage for each pool in Gt CO_2e. Arrows illustrate key net flows of carbon. The as-actually-managed and reduced-harvest scenarios have the highest withdrawal of atmospheric carbon and causes the least fossil emissions. The no-harvest scenarios perform worst and imply major shifts of fossil carbon to forest living biomass. The reduced-harvest scenario results in almost the same withdrawal from the atmosphere as the BAU scenario but leads to higher fossil emissions.

Comparing as-actually-managed scenario 1980-2019 with SKA15 2020-2059

When comparing the historical scenario 0 with future projections in SKA15, the results show a stable continued trajectory of forest growth, harvest and stock increase (Table 5, Figure 8). While actual historical data should only with caution be compared with future model projections, it is clear that the choices made for coming decades will have very similar consequences as those described above for the period 1980-2019. One difference is that the living biomass stock at the beginning of the period in 2020 is 40% higher than in 1980. This poses higher risks for forest damages for no-harvest options.

Table 5. Comparison scenario 0 (as-actually-managed) 1980-2019 with SKA15 – 90% harvest scenario 2020-2059

Scenario	**Total climate effect**[1]				**Fossil emissions**[3]	**Living biomass**			**Change in atmospheric carbon pool**
	Carbon storage	**Net fossil displacement**[2,3]	**(of which fossil emissions)**[2,3]	**Total**		**at end of period**	**increase since beginning of period**		
	Gt CO_2e	**Gt CO_2e**	**Gt CO_2e**	**Gt CO_2e**	**Gt CO_2e**	**Gt CO_2e**	**Gt CO_2e**	**%**	**Gt CO_2e**
As-actually-managed 1980-2019	-2,00	-1,54	0,16	-3,54	0,16	4,50	1,38	44	-1,84
SKA15, 90% harvest 2020-2059	-1,91	-1,88	0,16	-3,79	0,16	5,67	1,23	28	-1,75

[1] As per model proposed by Fargione et al. (2008). Negative numbers indicate (net) sink/displacement

[2] Net fossil displacement includes deduction of fossil emissions in the value chain. Fossil emissions are also listed separately in the table.

[3] No efficiency gains or changes in displacement effects were included for the future scenario

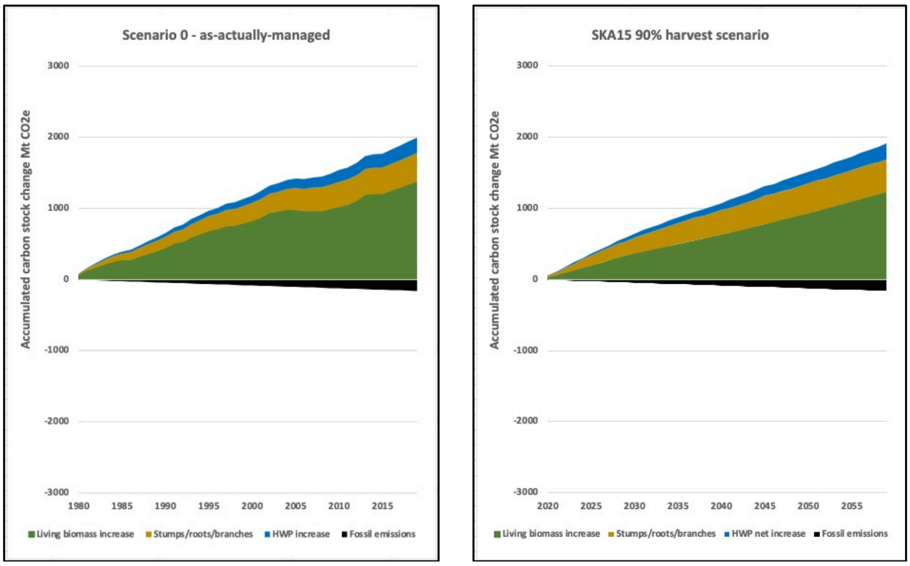


Figure 8. Comparison of carbon stock developments between scenario 0 (as-actually-managed) 1980-2019 (same as in Figure 6) with SKA15 – 90% harvest scenario 2020-2059

Sustainable development externalities to consider

Recalling that the Paris agreement target to limit global warming to *"..well below 2 ℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 ℃.."* is to be achieved "*..in the context of sustainable development and efforts to eradicate poverty*", it is relevant to discuss effects of scenarios on the wider set of sustainable development goals. These effects can be considered as externalities to the carbon-debt/carbon-parity model.

The no-harvest scenarios represent a stark deviation from the actually managed case which is the result of broadly agreed national forest policy over the past 100 years and subsequent development and growth of the forest-based sector. It is therefore important to identify and consider beyond-climate externalities of the no-harvest scenario that are not captured by the above model and illustration.

First, it is implicit in the model that a no-harvest scenario will cause higher fossil emissions. This is the consequence of not converting biomass into materials and products that displace fossil-based ones. It could be argued that the no-harvest scenario would be accompanied with lower overall consumption, thereby buffering for the lost fossil-free goods. However, lower consumption could similarly have accompanied the actually managed case. This paper does not attempt to model effects of lower consumption. If reduced climate impact is the purpose for lowering consumption, however, it would be reasonable to assume that there is a preference to prioritize reduced consumption of products with a higher carbon footprint.

Second, a no-harvest scenario would have significant implications at the national level on jobs, rural development, energy security, export revenues, corporate and property values, and the economy at large. In other words, such a scenario would have large and negative impact on a wide range of Sustainable Development Goals and Agenda 2030. Given that the Paris Agreement is framed within sustainable development, it is unlikely that a no-harvest scenario would be compatible with the 1.5 (or 2) degree ambition, even if it would be a positive climate action (which it is not). That said, given the assumption of unchanged consumption above, it is possible that part of the economic losses would be compensated by expansion of fossil-dependent sectors. It is not the purpose of this paper to make an econometric analysis of these impacts, however some key numbers of the Swedish forest-based sector are shown in Table 5. From the literature review (see above and Annex 1), it is clear that most studies of forest carbon debt have not considered such externalities.

Table 5. Key facts about the Swedish forest-based sector that would be severely implicated by a no-harvest scenario. Sources. Swedish Forest Industries, Swedish Energy Agency, Swedish Forest Agency, Corporate annual reports. Reference years 2018/2019

Employment in the forest-based sector	70,000 employees, including subcontractors, many in rural areas
Energy security	33% of net energy supply from bioenergy, almost all from forest biomass
Export revenues	SEK 150bn/yr (€14.5bn/yr), corresponding to 10% of total export revenues from Sweden
Corporate financial assets in the forest-based sector	>SEK 500bn (>€50bn) in reported assets for Swedish corporations in the forest-based sector (includes forest land in some cases)
Aggregated market value of forest land	c. SEK 1500bn (c. €150bn) based on current forest land sales

Third, and as an alternative to reverting to fossil fuels under the no-harvest scenario, forest harvest and forest industry may shift to other geographies. On one hand this could be an expression that the no-harvest scenario has no net effect if the forest-based sector simply shifts to other locations/countries. On the other, such shifts may be to regions where performance on both climate and environmental aspects may not be as progressive as in Sweden.

Fourth, a no-harvest scenario would quickly reduce access to forests for other uses and benefits, as most roads would not be maintained, and windfalls and fires would make forests less amenable and less safe to visit. This would have negative impacts on peri-urban recreation, hunting, berry and mushroom harvests, reindeer herding, and outdoor tourism business. As rural economies would suffer, service and infrastructure in rural locations would diminish, further reducing access to and benefits from forests.

Fifth, benefits to sustainable development by the forest-based sector can be indirect, very large and accrue far from the forest. Sanitation products leads to better health, as well as gender equality worldwide. Affordable housing and bioenergy are key factors in alleviating poverty and improving food security. Efficient packaging support logistics solutions that facilitate trade and reduce inequalities.

Turning to the scenario representing a 10% reduction of harvests, the consequences would obviously be less significant. However, also a 10% reduction of the forest-based sector may result in losses of:
- thousands of jobs, primarily in the rural/disadvantaged areas
- SEK 15 billion annually of export revenue
- a large share of renewable energy options in Sweden and beyond
- many SEK billions in capital losses from forest lands and forest industries.

Conclusively, reducing harvests from forests will have major effects on a wide range of socio-economic aspects related to sustainable development. Even if this would be justified from a climate change perspective (which this study shows it is not), these externalities must be taken into account in the policy debate and political decisions.

Beyond socio-economic externalities, environmental aspects beyond climate change mitigation are also important to consider, e.g.:

- Impact on biodiversity, or biodiversity potential of the different scenario. It is often argued in the debate that active forestry with harvesting is negative for biodiversity, pointing to, e.g., the Red List of threatened species. At the same time, observations from e.g. the national forest inventory show improvements in key habitat structures in recent decades and set-aside areas have increased since the 1990s. It is not a topic for this paper to review this further, but to flag it as an important externality to the model scenarios in this paper;

- Climate change adaptation of forests is of increasing concern. Again, it is not further analysed in this paper, other than noting that active forest management can offer a range of measures for adaptation, and may have to if future harvest scenarios are to be realized.

Discussion

Carbon debt, parity and payback time concept

The suggestion that forest harvests cause a carbon debt that will be repaid only over the long term has been promoted in the context of IPCCs calculation of remaining carbon budgets. As the argument goes, we don't have time to repay such debt and more trees should instead be left standing. Models originally used for land conversion to crop-based biofuel production have been extrapolated to other geographic regions and forest management regimes to try and exacerbate this position. However, a review of the literature for this study reveals that available research results have limitations in data, scope and are highly dependent on assumptions. In addition, externalities to modeled results have seldom been taken into consideration.

Despite the inconclusive knowledge base, many proponents in current debate on forestry strategies in, e.g., Sweden continue to suggest reductions of forest harvest as a suitable climate action.

Current analysis - methodology

The current analysis uses real-world data for the development of forests and delivery of forest-based products in Sweden covering the period 1980-2019. Basing the analysis on official and verified statistics provides a reality check to propositions made that a carbon debt accrues from forest harvesting.

While the accuracy of input data is unquestionably better than in most previous studies, some uncertainties still remain and should be subject to further analysis, e.g.:

- Impacts on soil carbon developments. Likely, active management for high production of wood, with accompanying higher turnover of biological material, generally leads to a higher rate of accumulation of soil carbon, and conversely no-harvest scenarios to a lower accumulation, as indicated by (SLU, 2019). For organic soils, carbon can leak if soils are drained to increase production, which is an opposite effect. The effects on soils from increased wildfires under no- or reduced-harvest scenarios are not well known;

- Future developments of forest stands that are not managed are not as well investigated as for stands that are actively managed, which means that it is difficult to predict how and at what pace the net carbon sink will deteriorate. Taking this to the landscape level increases the uncertainties as the incidence and severity of outbreaks of insect damages, windfalls and wildfires are difficult to predict. Assumptions of natural losses in this study are probably conservative. For example, it is unlikely that a doubling of the forest living biomass stock (scenario 1a) would result in a stable carbon stock condition – more likely this would be a situation with high risks of rapid deterioration;

- Investments in better plant material and application silviculture methods may increase production further, leading to higher storage and harvest. This will, however, also depend on the motivation (financial or other) by forest owners to invest in forest management;

- Climate change itself will impact forests. Overall, the ongoing warming is expected to increase production and thereby potentials for mitigating climate change. However, negative developments in some regions from droughts, insects or windfalls may also occur. Likely, active forest management is often a suitable way to handle climate change adaptation, as choices on species mix, rotation length and other treatments can be made;

- Fossil displacement (substitution) effects are not precise. Research in the field is limited as displacement is not part of official climate reporting, hence there is so far limited demand for standards and an improved knowledge base. At the same time IPCC scenarios imply a high degree of fossil displacement from forest-based products and energy. The assumption is this study is conservative and based on available research;

- Development of new materials, more efficient value chains in the bioeconomy and new solutions such as BECCS (Bioenergy with Carbon Capture and Storage) are outside the scope of this study, but may reinforce the case for an efficient forest-based sector as a means to achieve climate solutions at scale

A need to turn around the debate

Worryingly, the idea that forest harvesting causes a carbon debt has become an ”established fact” in contemporary Swedish and European forestry debate – despite being incorrect and/or implausible as shown in this study. A long series of such expressions were quoted above. One apparent representation of these propositions can be found in the recent Official Inquiry on forests (Government of Sweden, 2020, p.301). Here it is stated, with no reference or analysis, that “there is a certain implicit conflict between (..) increasing raw material (wood) production and maintaining or increasing forest carbon storage..”, thereby apparently accepting a simplistic choice between two options. Similarly, well developed arguments for climate benefits of active forestry are made in KSLA (2020, chapter 2), but references are still made to climate gains in the short term if no harvesting is made. Clearly, vague messages from confined modeling of carbon debts have influenced prominent forestry knowledge platforms in Sweden. Similar reasoning is found in the recent science – policy report by the European Commission(EC Joint Research Centre, 2021).

One recurring attribute in the forest carbon debt argument is that increased fossil emissions – implied by reduced harvesting – are not considered. This is possibly because the carbon debt model, as well as the sector structure in climate reporting more generally, set system boundaries that isolate the forest. Externalities to the biological forest system are thereby excluded from the analysis in most cases.

As shown in this analysis, the most obvious consequence of reduced-harvest scenarios of sustainably managed forests is that fossil deposits of carbon are merely shifted to living biomass storage, with no direct benefit in relation to the global climate. Arguing for reduced harvesting as a climate action is therefore similar to the argument for trading forest carbon offsets – essentially a justification for continued fossil emissions elsewhere with no net gain for the global climate.

Forests and forest-based products and energy are considered an important part of the climate change solutions. Erroneous conclusions on negative impacts of harvesting, such as by (Norton et al., 2019) are highly counterproductive.

Conclusions

- Results confirm that no carbon debt accrue in Swedish forestry. On the contrary a carbon asset is continuously being built up in the forest, in parallel with harvesting of biomass for climate-smart products;

- Further, no relative climate benefit for no-harvest scenarios over the actual case was found in the short term, despite commonly expressed views in the debate;

- One major consequence of the no-harvest and reduced-harvest scenarios relative to the as-actually-managed scenario is that fossil carbon deposits are withdrawn and used, while storage in forest living biomass is left unused and thereby increase. This can be seen as shifting fossil deposit storage to storage in living biomass. Aside of direct climate impact of the scenarios, storage in living biomass is obviously less stable than continued storage underground. Policy implications of such increased risks are however not further considered in this analysis;

- No-harvest scenarios, as well as scenarios that partially reduce current harvest levels would have severe and negative externality implications on the Swedish society. Jobs, rural development, capital assets (forest and corporate) as well as export revenues would likely be negatively affected;

- Based on the findings, there is no support for the proposition to reduce or eliminate harvests from Swedish forests as a climate action.

- On the contrary, the very large climate benefits that accrue from actively managed forests and manufactured products from the timber harvest are essential for achieving the required rapid reductions of fossil emissions.

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Annex 1. Reviewed literature

1. Synthesis papers

Synthesis paper	Findings (Key results)
Bentsen (2017)	The outcome of C debt studies lie in the assumptions. Methodological, not ecosystem and management assumptions, determine findings. Current development of C debt methodologies and their lack of consensus of the concept in itself is inadequate for informing and guiding policy development.
Buchholz et al. (2016)	The inclusion of wildfire dynamics proved most influential in determining C payback period compared to factors such as feedstock type, baseline choice, and the incorporation of leakage calculations.
Chatham House (2017)	1. The use of biomass for bioenergy can have negative impacts on the global climate. 2. Biomass is considered a carbon neutral energy source due to one or both of the following assumptions: First, that biomass emissions are part of a natural cycle in which forest growth absorbs the carbon emitted by burning wood for energy. Second, that biomass emissions are account for in the land-use sector and not in the energy sector, under international rules for greenhouse gas emissions.
EC Joint Research Centre (2014)	1. Use of stemwood from dedicated harvest for bioenergy would cause an actual increase in GHG emissions compared to those from FF in the short and medium term (decades). while it may start to generate GHG savings only in the long term (several decades to centuries). 2. The emissions increase of the forest bioenergy systems are more limited (in size and/or duration) with forest residues, thinning and salvage logging- if not otherwise used for other purposes 3. C savings can be immediate for above mentioned residual biomass and biomass from plantations established on agricultural or grazing land depending on counterfactual scenario. 4. Waste wood and industrial wood residues provide GHG saving in the short term. 5. Large variability in results of forest bioenergy fossil fuel parity times calculations depends on the many different characteristics of the systems compared and non-consistent modeling assumptions and approaches. 6.For adequate analysis economic and legal considerations in reference scenario must deal with a coherent storyline of the use of goods and services provided by forest (food, feed fiber etc.) 7.Natural disturbances and future changes in forests productivity ought to be accounted for. 8. Wood product substitution for fossil products needs different reasoning. 9. Biogenic C neutrality not valid under policy relevant time horizons.
EC Joint Research Centre (2021)	(Chapter 5: Sustainability of Forest Bioenergy) 1. It is possible to highlight win-win forest bioenergy pathways. These can both reduce greenhouse gas emissions in the short term while at the same time not damaging or even improving, the condition of forest ecosystems, 2. Collecting slash withing the limits of locally recommended thresholds could be used to generate energy without damaging forest ecosystems while likely contributing to reducing GHG emissions. 3. Afforesting former agricultural land with mixed species plantations or naturally regenerating forests would enhance the terrestrial sink even before producing biomass for material and energy uses and thus would contribute to CC mitigation, while at the same time improving ecosystems' conditions 4. Depending on local conditions, removal of course woody debris and low stumps could be detrimental to forest ecosystem and unlikely to reduce C emissions in short or medium term compared to FF. However, in climate areas with high decay rates stumps and debris could aid c emissions mitigation without damaging local biodiversity. 5. Converting natural and old growth forest to plantations for woody bioenergy would be very negative for local biodiversity and c emissions in short-medium term. This is also valid for naturally regenerating forests to high-intensity management plantations. 6. Voluntary standards and national guidelines are necessary but possibly not sufficient to mitigate the highlighted risks. 7. Through the LULUCF regulation 2018/841, the carbon impact of any change in management or wood use is reflected in the countries' EU climate accounts 8. Managing the risk of unintended outcomes (e.g. excessive use of forest biomass by economic operators, leading to LULUCF accounting debits at country level) requires, first and foremost, a greater awareness by countries of the REDII/ETS-LULUCF links and the associated trade-offs. This awareness should then be reflected in the national relevant plans (National Energy & Climate Plans), through coherent policies and financial incentives at national and local level, combined with a timely and reliable monitoring of the use of wood for energy production.

	9. As general principle, prioritizing residues and a cascade use of wood remains key for maximizing the positive climate impact of forest bioenergy. 10. On imported biomass, criteria should aim to maintain the same environmental standards applied in the EU
Helin et al. (2013)	To account for GHG emissions and the related climate impacts objectively, biomass C stored in the products and the timing of sinks and emissions should be considered in LCA.
Lamers and Junginger (2013)	Differences in the modeling framework and parameterization are the main distinctions between current temporal forest C analyses.
Miner et al. (2014)	1. "As long as land remains in forest, long-term carbon mitigation benefits are derived from sustainably managed working forests that provide an ongoing output of wood and other biomass to produce long-lived products and bioenergy, displacing GHG-intensive alternatives." 2. "The demand for wood keeps land in forest, provides incentives for expanding forests and improving forest productivity, and supports investments in sustainable forest management that can help offset the forest carbon impacts of increased demand." 3. Although forest bioenergy systems sometimes produce near-term increases in CO2, they typically result in lower cumulative CO2 emissions over time, and cumulative CO2 emissions, according to the IPCC, are the best predictor of future peak global temperatures.
Norton et al. (2019)	1. Current policies are failing to recognize that removing forest carbon stocks for bioenergy leads to an initial increase in emissions 2. The periods during which atmospheric CO2 levels are raised before forest regrowth can reabsorb the excess emissions are incompatible with the urgency of reducing emissions to comply with the objectives enshrined in the Paris Agreement. 3. Furthermore, we describe the current United Nations Framework Convention on Climate Change accounting rules which allow imported biomass to be treated as zero emissions at the point of combustion and urge their revision to remove the risk of these providing incentives to import biomass with negative climate impacts"
Ter-Mikaelian et al. (2015)	"Accounting for the GHG emission reduction potential of forest bioenergy must include the following: A. Forest carbon following biomass harvest for energy production (the forest bioenergy scenario); B. Forest carbon in the absence of demand for bioenergy (the forest baseline scenario); C. Life cycle GHG emissions (upstream FF emissions) from producing forest bioenergy (excluding GHG combustion emissions); D. Life cycle GHG emissions (including those from combustion) for the fossil fuel displaced by forest biomass (the reference fossil fuel scenario)."
Vanhala et al. (2013)	1. Forest bioenergy can cause net GHG emissions if harvesting decreases soil and biomass c stock. 2. “The holistic ecosystem level analysis of the carbon balance should include the carbon uptake in tree growth and the emissions of decomposition of soil organic matter controlling the sink/source dynamics of the ecosystem.” 3. “The carbon balance of any bioenergy production system must be assessed over the life cycle of the product; carbon accounting protocols for bioenergy production systems must quantify the net carbon emitted into the atmosphere and reductions in fossil fuel-derived carbon emissions achieved.”

2. Scenario models / case studies

Article	Key findings
Achten and Verchot (2011)	Land use change associated with biofuel production systems can have implications for the climate mitigation potential of biofuels. While each biodiesel system studied has a CC mitigation effect, the LUC creates a debt that requires 18 - 629 years to repay.
Achten et al. (2013)	Net emissions strongly depend on current land use biomass C stock, average biomass C stock of Jatropha rotations and seed yield of Jatropha.
Bernier and Pare (2013)	Bioenergy project using tree stems as bioenergy feedstock result in C debt repayment period of 90 years. Time for atmospheric C debt repayment of bioenergy projects is highly dependent on ecosystem-level CO2 exchanges.
Cherubini et al. (2013)	Climate metric choice can have a significant influence on the results.
Colnes et al. (2012)	(Section 2 : Atmospheric C Analysis) 1. As biomass demand increases with more facilities beyond the 22 modeled, the ability of the forested landscape to provide biomass supply and store carbon may become more limited, particularly in localized areas with strong demand. 2. The results indicated that the 17 existing biomass facilities were now generating and would continue to generate an improved atmospheric carbon benefit relative to FF technologies. 3. Using SE forests for the modeled expansion of power generation produced a significant long term atmospheric benefit, but at a short term atmospheric cost. (35-50 year carbon repayment time before yielding benefits.) 4. Efficiency of combustion technology was shown to be a critical factor influencing carbon emissions over time. 5. Thermal and CHP applications are significantly more efficient (5-10 years in similar studies) 6. The study also found that there is wide variability in carbon outcomes for different fuel types across different combustion systems. 7. The use of logging residuals when available from current harvests, leads to an improved carbon balance versus using standing roooundwood because of the higher relative carbon storage of pulpwood vs residuals. 8. Residue supply highly dependent on other parts of the wood production economy.
Dehue (2013)	1. If bioenergy system provides significant GHG emission savings by 2100, they can contribute to the 2 degree target, even if such systems would initially increase GHG-emissions. 2. To limit global warming to two degrees, all energy will have to come from renewable (or other C-free) sources by 2100.
Domke et al. (2012)	Initial C debt associated from forest harvest residues for energy which is repaid over time through decomposition emissions and ultimately reducing to solely emissions from harvesting and transport 190+ years after establishment.
Eliasson et al. (2013)	Time and area are crucial to C balance calculations, especially in regard to biofuels from low productive ecosystems with long rotation periods. Significant loss of C after harvest in single stand which requires decades for growth to pay back. Soil C losses and gains in landscape perspective become evenly distributed over time.
Fargione et al. (2008)	Converting native habitats to crop–based biofuel plantations creates a carbon debt by releasing 17 to 420 times more CO2 than these biofuels would provide by displacing fossil fuels. Biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural incur little or no carbon debt.
Goodwin et al. (2020)	1. Non-linear relationship between treatment intensity and carbon stability 2. Drought mortality increased dead tree and surface fuel carbon in all treatments, contributed to higher second-entry burn emissions for two of the three burn treatments when compared to the first burn. 3. C debt of these forests will become increasingly unstable as C carrying capacity adjusts to severe drought events. 4.Managing the C debt with prescribed fire will help reduce the risk of additional mortality from wildfire, but at an increasing carbon cost for forest management.
Gunn et al. (2012)	Carbon accounting of woody biomass as energy source ought to be reconsidered as current approaches risk creating incentives for bioenergy production that may emit more CO2 than the FF alternatives over bioenergy chain life cycle and considering indirect pay-back effects
Hektor et al. (2016)	1. “Biomass harvested under sustained forest management is CO2 neutral (or better).” 2. Prolonged rotation periods would not reduce atmospheric CO2 in the long term, as the total C capacity of forest decreases. 3. Compared to coal, biomass may be regarded as climate neutral, provided adequate comparison. 4. In most countries applying sustained forest management, biomass production exceeds the present harvesting and utilization. 5. Given sustained forestry, efficient measures to reduce the CO2 net emissions are: Increase market demand for biomass in the energy sector, increase market demand for wood products and fiber, Increase intensity of forest management.
Holtsmark (2010)	1.Increased harvest of a boreal forest by 30% creates a biofuel carbon debt that takes 150–230 years to repay. 2. Permanent increase in the harvest results in a permanently lower forest carbon stock.

Article	Key findings
Holtsmark (2012)	1. Increasing the use of wood from a boreal forest to replace coal in power plants will create a carbon debt that will only be repaid after ca 190 years.” 2. “If the wood is used to produce second-generation liquid biofuels and replaces fossil diesel, the payback time of the carbon debt is estimated to be 340 years.”
Jonker et al. (2014)	1. C debt repayment / C offset parity point strongly varies on (a) the management system and (b) the methodological choices. 2. Payback times range from <1 year (landscape) to 27 years (stand level) and offset parity points range from 2–106 years. 3. C balances are region specific. 4. Main influencing factors were: “yield, carbon replacement factor, system boundaries and the choice of reference scenario”
Kallio et al. (2013)	Decrease in forest C sinks due to increased harvests cannot be offset by avoided FF emissions within the time frame considered. 2. Some welfare is reallocated from the forest industry, energy sector, and taxpayers to forestry and forest owners.3. Using logging residues for bioenergy should be preferred to coal or peat.
Leturcq (2020)	1.The substitution of wood for other fuels and materials, are overestimated.
Madsen and Bentsen (2018)	The results corroborate findings of a carbon debt, with a payback time of one year after conversion. GHG emissions are reduced to 50% relative to continued coal combustion after about 12 years. Residue biomass are an effective means for CC mitigation.
McKechnie et al. (2011)	1. Application of LCA method reveals substantial reduction in forest carbon due to bioenergy production. 2. For all cases, harvest-related forest carbon reeductions and associated GHG eissions initially exceed avoided FF-related emissions, temporarily increasing overall emissions. 3. In the long term, electricity generation from pellets reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16-38 years depending on biomass sources. 4. Ethanol produced from standing trees increases overall emissions throughout 100 years of continuous productions 5. Ethanol from residues achieves reductions after 74 year delay. 6. Forest carbon more significantly affects bioenergy emissions when biomass is sources from standing trees compared to residues and when less GHG intensive fuels are displaced.
Malcolm et al. (2020)	1. The type of fossil fuel for substitution had the strongest effect on payback periods. 2. Clear-cut-based management of boreal primary landscapes to produce wood pellets to replace fossil fuels in electricity generation will result in net emissions of greenhouse gases to the atmosphere for many decades. 3. The steady-state store of C in the landscape after a first rotation of harvesting was strongly influenced by the length of the rotation period."
Mitchell et al.(2012)	1. Times required for bioenergy substitutions to repay the C Debt are usually much shorter (< 100 years) than the time required for bioenergy production reach parity point. 2. Effectiveness of substituting woody bioenergy for fossil fuels is highly dependent on bioenergy conversion efficiency factor e.g., C emissions from harvest, transport, and firing of biomass 3. Initial landscape conditions and land-use history fundamental to determine payback time of C debt
Nabuurs et al. (2017)	1. C debt does not occur. i.e. the largescale average C stocks in the forest are not reduced. 2. Parity effect observed though eventually compensated for. However, it took long, especially if final fellings were increased for bioenergy. 3. In case of increased thinnings, the parity equality was reached within 80 years compared to burning coal. Removal of harvesting residues was often compensated within 1 decade.
Naudts et al. (2016)	1. Despite afforestation, Europe’s forest has accrued a C debt of 3.1 petagram since 1750. 2. Not all forest management contributes to CC mitigation.
Pingoud et al. (2016)	1. Though Finnish forests remain C sink in the considered scenarios, increasing forest bioenergy may increase atmospheric CO2 concentrations compared to baseline and FF use. 2. Net emission depends on: forest-growth, residue-decay dynamics, and on the timing and evolution of harvests.
Repo et al. (2015)	In the short term, “extending the current sustainability requirements to solid bioenergy does not guarantee efficient reductions in GHG emissions.” In the longer-term, bioenergy from forest harvest residues may contribute to low-emission energy systems. 2. harvest residue removal reduced the carbon stocks of litter and soil on average by 3% over the period from 2016 to 2100. 3. 60% reduction in CO2 emissions, compared to FF, achieved with continuous forest bioenergy use for heat production in most European countries after 60 years. Over 80 years to reach to the 60% target in electricity generation.
Romijn (2011)	1. Jatropha can sequester atmospheric carbon when grown on wastelands or degraded conditions. 2. Jatropha introduced on land with high biomass and medium/high soil C results in significant emissions with C debt of more than 30 years 4. Soil C significant for results.

Article	Key findings
Walker et al. (2010)	- Replacement of FF in thermal or combined heat and power applications typically has lower initial carbon debts for utility-scale biomass electric plants. - Absolute magnitude and timing of CD and C Dividends is sensitive to how landowners decide to manage their forests. - Carbon debts per FF and technology: Oil#6+Thermal/CHP= 5 yrs Coal, Electric = 21 yrs; Gas, thermal = 24 yrs; Gas, Electric = >90 yrs - Comparing 40 years of continued biomass emissions with 40 of FF, shows replacement of oil-fired thermal/CHP capacity with biomass thermal/CHP fully offsets CD and lowers GHG levels (approx. 25% lower over the period under a rapid recovery scenario) - For biomass replacement of coal fired plants, net cumulative emissions by 2050 are approx. equal to what they would have been burning coal - For replacement of Natural Gas cumulative total emissions are substantially higher with biomass electricity generation. - Future supplies of forest biomass available for energy production depend heavily on the prices that bioenergy facilities are able to pay for wood. - The upper end of the range for Massachusetts forest biomass supplies under the high-price scenario is approx. 885 000 green tons per year. - Sustainability issues at landscape level include: aesthetic impacts on recreation and tourism and the longer-term health of the wood products sector of the economy. - Stand scale sustainability impacts include maintenance of soil productivity and biodiversity.
Walker et al. (2013)	1. Wide variability in the magnitude of carbon debts across different biomass technologies combined with FF capacities that are displaced. 2. Carbon recovery times can differ by decades depending upon assumptions about (a) the intensity of harvests; (b) the silvicultural prescriptions and cutting practices employed; (c) the fraction of the logging residues removed from the forest for biomass; and (d) the frequency at which landowners re-enter stands to conduct future harvests.
Withers et al. (2015)	1. "The carbon breakeven time underestimates the breakeven time of economic damages and overestimates the breakeven time of temperature change and radiative forcing." 2. "These breakeven times indicate that the temperature change resulting from the managed forest carbon debt exceeds the temperature change caused by fossil fuels for nearly 50 years. In addition, society sustains greater economic damages than it would have with fossil fuels for at least 100 years."
Zanchi et al. (2012)	1. "The emission benefits of bioenergy compared to use of fossil fuel are time-dependent." 2. The assumption that bioenergy always results in zero greenhouse gas emissions compared to use of fossil fuels can be misleading, particularly in the context of short-to-medium term goals. 3. Sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term. 4. Different woody biomass sources have various impacts in the short-medium term. 5. Use of forest residues that are easily decomposable can produce GHG benefits compared to the use of fossil fuels from the beginning of their use and that biomass from dedicated plantations established on marginal land can be carbon neutral.
Zetterberg and Chen (2015)	1. We find that the climate impacts from the use of branches, tops, and stumps depend on how fast the combustion related emissions are compensated by avoided emissions from leaving them on the ground to decompose. 2. We find that the time perspective over which the analysis is done is critical for the estimated climate impact of biofuels. 3. We find that establishing willow may result in a net accumulation of carbon in the soil and a net uptake of atmospheric carbon compared to the reference case of crops. 4. The choice of reference scenario is critical for the estimated climate impacts.

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