EUROPEAN FOREST INSTITUTE

Forest-based bioeconomy and climate change mitigation

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Executive summary

The 2015 Paris Agreement aims to ensure that the global average temperature increase remains below 2 ˚C above pre-industrial levels and pursues further efforts to limit the temperature increase to 1.5 °C. Achieving these goals requires major societal and economic reforms to significantly reduce anthropogenic greenhouse gas (GHG) emissions and increase carbon sinks. Forests and forestry play an essential role, as they provide natural carbon sinks and their products can substitute for emissions-intensive materials, thereby reducing emissions.

This study provides an overview of the role of the forest-based sector in carbon management, from carbon sequestration to carbon storage in forests and wood products, to material substitution for emissions-intensive materials. Quantifying how these forest roles interact is not simple, and there is relatively limited understanding of the issue, especially in the public debate. This study presents an overview of:

- the *carbon dynamics in managed forests where harvest takes place*, as well as considering other climate impacts, such as the connection between harvesting and adaptation to climate change, and the effect of harvesting on biodiversity
- the *climate contribution of harvested wood products*, including carbon storage and their role in substitution of non-renewable and GHG-intensive materials, for example in sectors like construction and energy
- how *forests and the forest-based sector can contribute to climate change mitigation through Climate-Smart Forestry* that holistically considers climate change mitigation and adaptation, as well as biodiversity and ecosystem service provisioning.

Consideration of all climate-forcing agents (biochemical and biophysical) related to forest use is necessary to define credible policy and management strategies for mitigating climate change. In addition to carbon sequestration and storage, forests provide a wide range of benefits to society, and the maintenance and improvement of these functions is a fundamental part of sustainable forest management.

The carbon balance of forest landscapes is affected by many factors, including changes in the intensity of biomass harvest. Increased harvesting intensity of forests generally reduces the amount of carbon stored in forest biomass. A decrease in forest carbon caused by additional harvest may lead to an increase in atmospheric carbon concentrations – depending on the counterfactual development of forests if harvest would not have occurred, as well as on storage and substitution effects through the use of wood products.

Short-lived wood products and uses which provide a minor substitution benefit (e.g., energy) generally provide small or no benefit to climate change mitigation. However, long-lived wood products provide carbon storage opportunities by stockpiling previously fixed carbon from the atmosphere for decades to centuries. Furthermore, using wood-based products to substitute high-emission intensity alternatives could yield significant climate benefits; however, technological change could reduce the emission intensity of competing products, which would reduce the substitution factors. Comprehensive analyses which consider all aspects of forest use should be used to weigh the trade-offs between different strategies and aim to reduce the amount of fossil fuel that is extracted.

As well as carbon sequestration and storage, forests are of key importance to biodiversity and provide a wide range of benefits to society, and the maintenance and improvement of these functions is a fundamental part of sustainable forest management. Climate-Smart Forestry is an integral approach to sustainable forest management that combines climate change mitigation with the need to adapt to the impacts of climate change. It offers a holistic approach, reconciling and aligning mitigation, adaptation needs as well as maintaining or enhancing biodiversity and ecosystem services to guarantee resilient forests and a positive contribution by forests and the forest-based sector towards GHG emission mitigation today and in the future.

Key messages

The contributions of forestry and the forest sector to mitigating climate change could be optimized through some of the following actions:

- To strengthen the contribution of forests and the forest-based sector to climate change mitigation, a holistic approach is needed that considers carbon storage in forest biomass, soil and wood products, substitution effects, as well as potential leakage effects. Moreover, sustainable, climate-smart forest management must ensure the current and future supply of raw materials, protect and improve biodiversity, and preserve soil and water quality, for a balanced contribution to all ecological, economic and social functions.
- In managed forests, forest carbon sequestration should be strengthened by stimulating forest productivity (e.g., tree species and provenance selection, thinning and harvest regimes) and by strengthening the resilience of forests to climate change (e.g., by increasing species diversity). This should be achieved by sustainable forest management practices that are locally relevant and which consider future climate conditions.
- Forest harvesting and carbon storage should be analyzed in conjunction with the other functions that forests fulfill. Reducing wood harvest increases carbon storage in forest ecosystems in the short term, and may bring benefits to biodiversity, soil and water quality. However, it may compromise economic benefits from forests, and the increase of carbon storage is valid until the carbon sink saturates in the forest. In addition, forest management should also consider that natural disturbances such as storms, wildfires and pests are expected to increase under climate change conditions, having immediate economic impact regarding wood applications, and eventually leading to carbon release to the atmosphere.
- The sustainable use of wood for materials and products should follow the principles of cascade use. In this approach wood is used, reused and recycled, thereby extending the material's lifetime within the system. In addition, wood should be used for products that store carbon for as long as possible, and for products that provide large substitution benefits by avoiding emissions.
- Forest-based bioenergy has a role in the transition of the energy sector towards emissions-free energy production. When using woody biomass for energy purposes, preference should be given to post-consumer wood and forest residues that are not suitable for the production of other materials and which do not lead to additional harvest.

1. Introduction

The Paris Agreement aims to ensure that the global average temperature increase remains below 2 ˚C above pre-industrial levels and pursues further efforts to limit the temperature increase to 1.5 °C. Achieving these goals requires major societal and economic reforms to significantly reduce anthropogenic greenhouse gas (GHG) emissions and increase carbon sinks. Forests and forestry play an essential role in this context as they provide natural carbon sinks and their products can substitute for emissions-intensive materials, thereby reducing emissions.

The management of carbon flows between reservoirs in the Earth's system forms the basis for climate change mitigation. A substantial reduction in GHG emissions to the atmosphere is needed to limit global warming. The most important climate change mitigation measure is the decarbonization of the economy, achieved through a shift of energy, industry and transport systems to renewables, so that fossil fuels remain underground (Cowie et al. 2021). This study presents the potential role of the forest-based sector in carbon management, from carbon sequestration to carbon storage in forests and harvested wood products (HWP) to material substitution.

Chapter 2 presents an overview of the carbon implications of harvesting on carbon dynamics in forests. We discuss the carbon dynamics at the stand, landscape, and global levels. We also present considerations about other climate impacts, the connection between harvesting and adaptation to climate change, and the effect of harvesting on biodiversity. Chapter 3 discusses the climate contribution of HWP, with an overview of carbon storage in HWP and their role in substitution of non-renewable and GHG-intensive materials. We include estimations of climate change mitigation potential through substitution in relevant sectors, such as construction and energy. Chapter 4 discusses how the forest-based sector can contribute to climate change mitigation and adaptation using Climate-Smart Forestry (CSF) as a holistic approach. We present an overview of CSF measures that can be adapted according to the geographical regions and forest management objectives. The final chapter presents conclusions on how the contribution of forests and the forest-based sector towards mitigating climate change could be optimized.

2. Implications of forest harvesting on forest carbon dynamics

2.1 Role of forests in carbon dynamics

Forest land plays an important role in the global carbon cycle, and human interventions together with natural disturbances have a profound influence over carbon sink strength (Pan et al. 2011). Forests remove carbon dioxide (CO_2) from the atmosphere through photosynthesis and store carbon in tree biomass (i.e., stems, branches, foliage, roots). Through litterfall or mortality, part of this carbon is transferred into soils in which the material is slowly decomposing. Through decomposition, the CO_2 is eventually returned to the atmosphere and the rate by which this happens is governed by climate and the availability of decomposer groups (Seibold et al. 2021). In the case of harvesting, stems and sometimes also branches and roots are removed from the forests and used for wood products and energy. Harvest losses and tree parts that are not removed (e.g., branches, foliage, roots) also enter the soil and eventually decompose. When wood is used for energy, its carbon is returned immediately to the atmosphere during combustion. When wood is used for products, the carbon bound within can be transferred and stored in man-made reservoirs (e.g., buildings; Churkina et al., 2020). Such reservoirs can store carbon for decades or even centuries, after which the carbon eventually returns to the atmosphere through decomposition or combustion at the end of the product life (Figure 1).

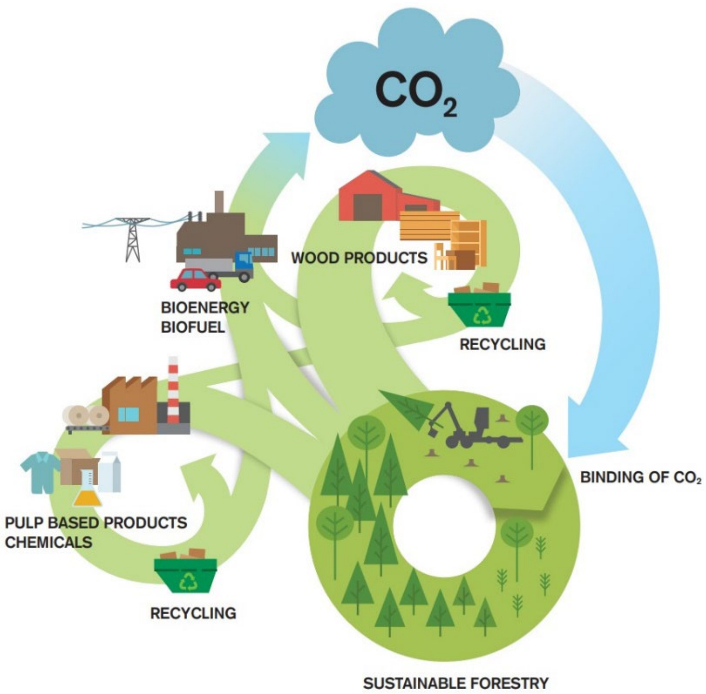

Figure 1. Carbon flows in the sustainable forest-based bioeconomy (Source: Sveaskog, cited by Berndes et al. (2016))

practices, afforestation, reforestation and reduced deforestation affect carbon sequestration in forest ecosystems.

2.2 Assessing carbon flows and impacts

Assessing the large carbon flows between the biosphere and atmosphere is complex. This is because the balance between carbon uptake and release that is affected by respiration, natural disturbances and human activity changes over time. For example, one challenge is that the changing climate is expected to affect forest productivity and bring unexpected events (e.g., wildfires, insect outbreaks) that could put carbon stocks at risk (Anderegg et al. 2020; Seidl et al. 2014). Consequently, it is uncertain how forests can best contribute to climate change mitigation in the future.

To measure the carbon implications of harvesting, it is necessary to estimate the total GHG emissions resulting from a system. In assessments, the outcome is largely dependent on the scope, the temporal and spatial scale, and the selection of the reference scenario (Berndes et al. 2016).

The *scope* depends on the main objective of the study. Studies can focus on the impact of specific forest operations on forest stands or expand the system boundaries to estimate net climate impacts of complex systems. Important factors are whether the forest system is considered in isolation or with interactions between forest management, policies and the development of carbon stocks and product substitution.

The considered *timeframe and starting point* of accounting are key, because of the time dependent characteristics of the assessed systems. In studies that start accounting at the point of harvest there will generally be a pulse in emissions followed by slow uptake into growing biomass. This temporary increase in atmospheric carbon is sometimes referred to as 'carbon debt'.

The *size of the study area* also affects the results. When considering smaller areas, such as individual forest stands, assessments can represent the reactions of forest systems to specific events. However, because there are many methodologies to evaluate the forest carbon balance after harvesting, making comparisons at the stand level can be misleading (Berndes et al. 2016). Instead, the impacts can be estimated by comparing studies which consider the landscape level where there are multiple stands with different age classes (Cintas et al. 2016; Cowie et al. 2021).

Defining a *reference scenario* is required to measure the impacts of a decision, instead of estimating the total carbon flows. This hypothetical baseline can reflect how flows would develop in the absence of specific policy instruments or in some other likely outcome (Soimakallio et al. 2015). It may be that the most useful reference scenario includes disturbance regimes induced by climate change, so that the mitigation potential of forests is not overestimated. Ultimately, the future is unknown, but a baseline scenario can be a useful tool against which end-users can compare and contrast the outcomes in different futures. One example of an approach for defining baselines is the Forest Reference Level, which has been developed for guiding policy in the EU. In this approach, scenarios for how forests would develop under "continuation of current management practices and intensity" are produced, based on harvests that were realized during a historical reference period. This baseline scenario makes it possible to measure the impact of future management changes regardless of changes caused by forest structures (e.g., age development and "legacy effects"). This approach promotes the active management of land under management (Grassi and Pilli 2017).

2.3 Forest carbon dynamics at stand level

Studies that assess the temporal flows of carbon from a single-stand perspective typically start accounting at the point when biomass is harvested and diverge in their use of assumptions for management regimes (e.g., collection of residues, planting and thinning). In a hypothetical scenario, the carbon contained in a forest stand will increase initially but the accumulation will level off until it reaches a plateau where emissions and removals are roughly balanced.

For individual forest stands under management, the temporal dynamics are typically characterized by long periods of biomass growth and short intervals of biomass loss (Figure 2). This interval between the establishment of a stand to the final felling (i.e., the rotation period) varies between a few years for fast-growing species to more than 100 years (Schelhaas et al. 2007). The rotation period and thinnings carried out during this time can be used to regulate the size of forest carbon stocks (Nabuurs et al. 2013; Liski et al. 2001).

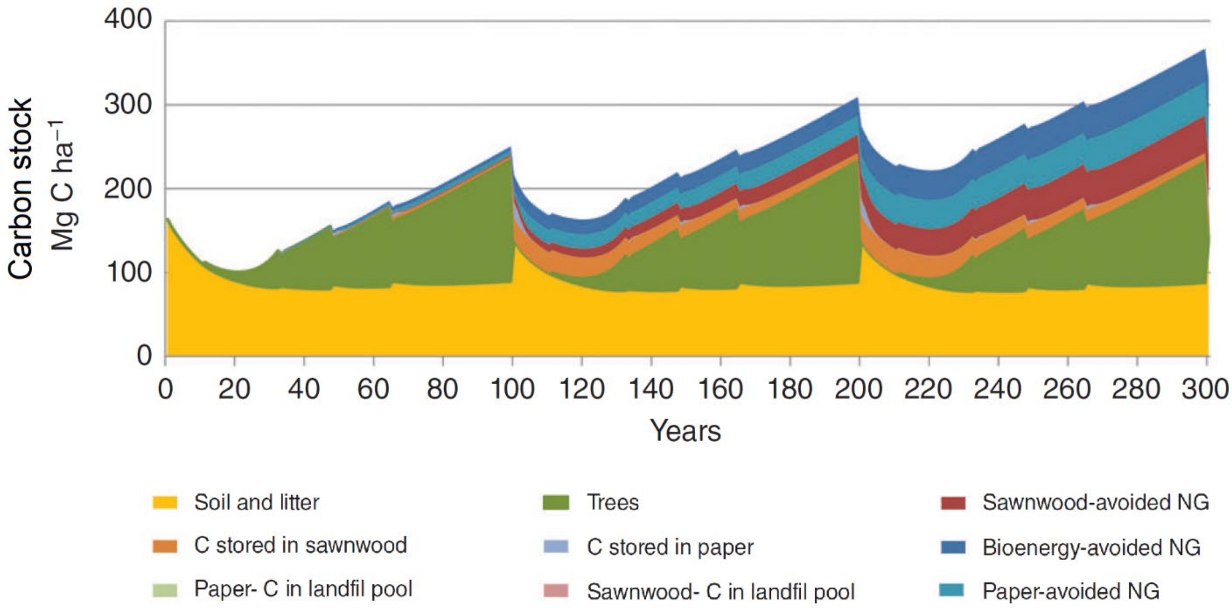

Figure 2. Stand-level carbon dynamics in a scenario with extraction of stemwood and residues (Cintas et al. 2016).

Both natural and managed forests can play important roles in removing CO_2 from the atmosphere. It is possible for stands to maintain a high sink strength for centuries if the forest stand density continues to increase as a result of small-scale disturbances (Luyssaert et al. 2008). However, when the stand is left to grow so that it reaches older age classes, it generally exhibits a slow-down in productivity (Gundersen et al. 2021). Still, there are uncertainties related to the accumulation of carbon (Zhou et al. 2006; Stephenson et al. 2014) and drivers of productivity (Jiang et al. 2020).

Harvesting of roundwood lowers sequestration by reducing growth (net primary production). This phase is typically followed by increased sequestration by remaining trees through reduced competition for resources such as light, water and nutrients. Collection of harvesting residues (e.g., treetops and branches) for bioenergy affects soil nutrient status and acidity, and it could reduce soil carbon. At the same time, this could be offset by increasing storage in standing trees (Achat et al. 2015). A few decades after harvesting takes place, a new stand is established so that the sequestration rate recovers and increases.

2.4 Forest carbon dynamics at landscape level

Harvesting of biomass generally leads to reduction in sequestration and carbon stock size on the level of the individual forest stand. When considering larger areas, such as a forested landscape, there can be multiple stands that are harvested at different times. In this case, the temporary reduction of forest cover can be balanced by carbon uptake in surrounding stands that are left to grow (Figure 3). This is the principle of sustainable forest management, which aims to provide a sustainable yield, while considering economic, social and environmental dimensions. In this approach, management is adapted to each individual site, and the production of wood relates to the demand for sawlogs, pulpwood, and wood for energy. This means that the forest carbon balance at the landscape level depends on a variety of factors, such as forest management practices, timing of harvests and the total area where management is applied. Recent shifts in societal priorities have led to questions about how forests should be used in the future, and it is unclear how to balance societal demands and political necessities with the requirements of multifunctional, sustainable forest management (Köhl et al. 2021).

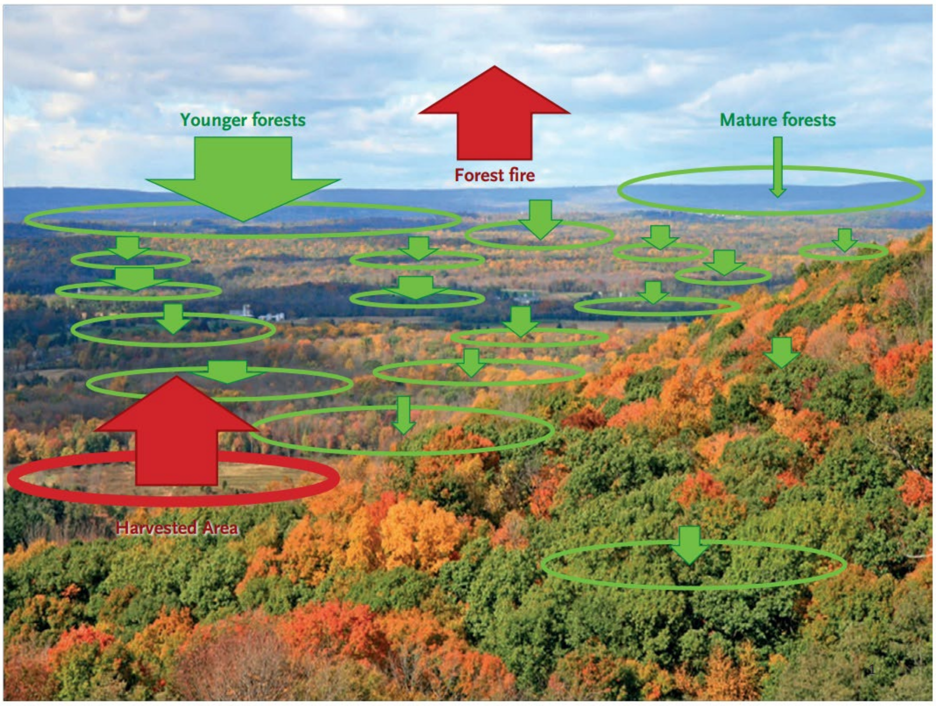

Figure 3. Many factors contribute to the net carbon balance on the forest landscape. This figure illustrates the size of fluxes caused by different factors, and how carbon emissions (red arrows) are counteracted by the uptake of carbon elsewhere (green arrows) (Berndes et al., 2016).

Balancing contributions to climate change mitigation with other management objectives is difficult, as decisions such as changing the harvest rate (i.e., amount of roundwood, residues, stumps that are removed) or introducing new tree species can conflict with other objectives such as biodiversity and recreation (Verkerk et al. 2014). On the other hand, this could lead to benefits outside the forest, and strategies that temporarily reduce the forest carbon could also be part of a long-term mitigation strategy e.g., to strengthen forest resilience by introducing seedlings that are better adapted to climate change. Successful strategies need to weigh the possible consequences of decisions in all sectors.

Many studies have aimed to fill this gap by using a holistic modelling approach to assess the climate impacts of different policy and management strategies. This has mainly been done by assessing the biochemical effects (Kalliokoski et al. 2020). Studies define different forest management regimes (e.g., variation in harvest intensity and rotation length) and map carbon flows between a defined forest area and the atmosphere. Resulting changes in HWP pool and emissions that are avoided by using wood-based materials to substitute other products are often also considered (Soimakallio et al. 2021; Rüter et al. 2016; Braun et al. 2016; Gustavsson et al. 2017; Seppälä et al. 2019).

2.4.1 Comparison of selected studies

When taking study-specific assumptions into consideration, existing explorative studies can be compared to offer insights into how harvesting rates could change, and what the impact would be on carbon balances. Within the country-level publications we reviewed, a variety of approaches was adopted for projecting the changes in the harvest and forest carbon stocks. Detailed scenario assumptions and results from the model runs are shown in Table A1 in the appendix. We compared how increased or reduced biomass extraction affects the development of forest carbon stocks when compared to a given reference scenario.

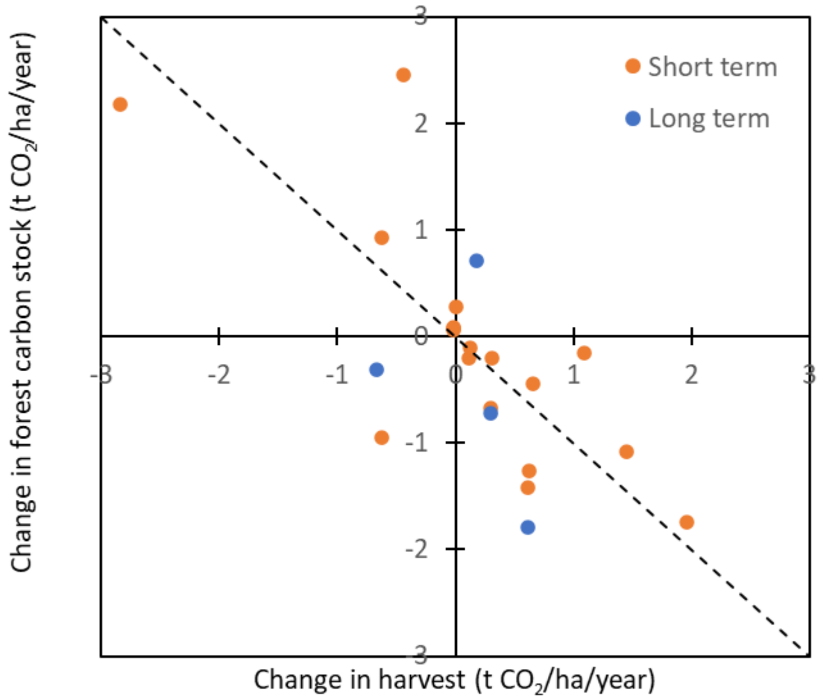

Figure 4. Results from study comparison (see appendix for details). Comparing the impact of changing harvest rates on carbon accumulation in the forest carbon pools (excluding HWP) over short-term (10-30 years) and long-term (50-100 years). Note: Positive values indicate increase and negative values indicate decrease in parameter.

As shown in Figure 4, the accumulation of carbon in the forests is directly affected by the harvest intensity. Extracting more biomass generally reduced the amount of carbon that is stored in forests, while there were few datapoints for reduced biomass extraction. Based on the comparisons we made, some studies anticipated that extracting additional biomass could reduce the sink, leading to a loss in forest carbon storage that is larger than the additional amount harvested. This was observed in the short term for two studies (see Bösch et al. 2017; Seppälä et al. 2019) and in the long term for one study (see Seppälä et al. 2019). In the latter, high substitution factors and a reduction in emissions from the HWP pool could be needed to offset the negative impacts of increased harvest rates. Some studies showed that forest carbon retention could be improved by extending the rotation period (Jevšenak et al. 2020; Bösch et al. 2017) or changes in silvicultural practices (Gusti et al. 2020). The inclusion of improved forest management activities, such as fertilizing, managing competition for resources, introducing species with higher productivity and changing seedling density could also increase forest carbon storage at the same time that biomass harvest is intensified (e.g., Gustavsson et al. 2017). Some studies considered changes in disturbance rate (Jevšenak et al. 2020) and climate change effects on productivity (Gustavsson et al. 2017), but the interaction between management, climate change and disturbances was not included and is seldom considered (Reyer et al. 2017).

2.5 Forest carbon dynamics at global level

Improving forest management, afforestation, reforestation and preventing deforestation are important measures for achieving climate targets, but the enabling conditions and barriers that affect the pathways towards set targets vary greatly between regions and countries. In the global economy, changes in sequestration in one defined area can have positive or negative effects on sequestration elsewhere. For example, if one country's domestic demand for forest products would increase, then imports of commodities could cause deforestation other parts of the world. This could also be caused by policies that incentivize carbon sequestration (Nepal et al. 2013) or otherwise affect the amount harvested in any defined area. The problem is relevant to consider in discussions about how sustainably managed forests should be utilized for climate change mitigation (Kallio and Solberg 2018). To prevent degradation of carbon stocks caused by export-markets, and to avoid that emission reductions in one region transfers embodied emissions elsewhere, a combination of supply- and demand-side policy measures could be required (Henders et al. 2015).

2.6 Other considerations

2.6.1 Other climate impacts

The climate impact of forest harvest is often assessed through its effects on the exchange of CO_2 with the atmosphere, known as biochemical effect. Changes in forest cover can also affect the surface energy budget through biophysical effects, namely by modifying the amount of incoming solar energy that is reflected and absorbed (albedo), evapotranspiration and surface roughness. Part of these impacts can be expressed in terms of 'radiative forcing', but there are significant uncertainties related to their quantification. The biophysical effects affect the climate over a shorter timescale when compared to biochemical effects, and often have local impacts on temperature and precipitation (Perugini et al. 2017).

Extensive and continuous forest cover, such as dark coniferous forests in Northern Europe generally lower the albedo and have a warming effect. The reflectivity is higher for deciduous trees and herbaceous vegetation, but it is even higher for open land, sand or snow. From this point of view, forest harvest, which directly affects reflectivity by reducing forest cover, could have a cooling effect. However, forest ecosystems also regulate evaporation and transpiration of water, and emit biogenic secondary organic aerosols that may lead to cloud formation, reflect the radiation, and lead to cooling (Cerasoli et al. 2021). The net outcome of these biophysical processes is highly uncertain and depends on the latitude, season, cloudiness, and forest management. This makes it difficult to quantify the net effect on global climate (Bonan 2008).

2.6.2 Harvesting and adapting forests to climate change

It is uncertain how forests will respond to changing local conditions (e.g., precipitation, temperature, extreme events) brought by ongoing climate change, and it may be necessary to enhance the ability of European forests to adapt. For example, this could include treating stands to increase their resilience (ability to absorb change and disturbance but still maintain the same functions).

A promising adaptation approach is to shape forests to lower susceptibility to disturbances and enhance their ability to recover from them. This could complement conventional disturbance risk management that aims to suppress disturbance spread (e.g., by sending airplanes to extinguish fires or trying to contain bark beetle outbreaks) (Lindner et al. 2020). Harvesting is one of the measures that can be used to support a regional or national forest policy (Duncker et al. 2012). In this way, the canopy can be opened or the whole tree stand replaced, allowing tree species more suited to the expected climate to be introduced (Jandl et al. 2019).

2.6.3 Harvesting impacts on biodiversity

In addition to contributing towards mitigating climate change, forests are important for maintaining and enhancing biodiversity. Most European forests are managed to maintain multiple functions, but around 15% of European forest land is protected with the objective of protecting biodiversity (Lier et al. 2020). Assessments that consider the impact of changing harvest rates on the provisioning of ecosystem services face similar difficulties to assessments on the impact on the forest carbon balance; namely that the differences in methodology (spatial- and temporal scale, reference scenario etc.) between studies can lead to different results. Assessing biodiversity considerations on a stand level is difficult due to dynamics that are continuously changing. Landscape-level assessments can be used to get an overview of impacts on species populations, but it is not only the sum of stand-level consequences, as there are landscape-scale processes as well (Ranius et al. 2018).

All types of management change affect the properties of forests, and studies have reported that changes could have both positive and negative effects, or no effect on species populations. In general, shifting towards intensified forestry could change habitat structures which are important for deadwood-dependent species and these species can most effectively be retained in unmanaged forests (Chaudhary et al. 2016; Ranius et al. 2018). The impacts of management change can be described in terms of trade-offs and synergies, and the outcome for ecosystem conditions can be assessed to find win-win, lose-win and lose-lose situations. Benefits can arise from different forestry activities, for example when carbon stocks have been degraded.

3. Climate contribution of harvested wood products

Forests make a strong and important contribution to meeting the Sustainable Development Goals (FAO and UNEP 2020). Sustainable wood production and use can be a key component of sustainable development, especially if multiple-use forest management is combined with other activities that contribute to sustainable landscapes (e.g., energy, employment, economic growth, sustainable cities, more resilient infrastructure, reduced ecological footprint, and climate change mitigation). Support for all of these initiatives can be found in improving the sustainability of timber production, its linkages to other sectors and the climate efficient use of HWP.

The use of wood products affects GHG balances in several ways (Sathre and Gustavsson 2009):

- the physical storage of carbon in forests and wood material — C-storage
- the fossil energy used to manufacture wood products compared with alternative materials
- the avoidance of industrial process carbon emissions such as in cement manufacturing — C-substitution
- the use of wood byproducts as biofuel to replace fossil fuels
- the possible carbon sequestration in, and methane emissions from, wood products deposited in landfills — GHG-emissions from disposal

To understand the carbon flows between forest and HWP pools and associated potentials for climate benefits, it is important to quantify carbon storage in HWP, carbon substitution and GHG emissions from disposal of HWP under different conditions. Through a critical review of currently available literature, this chapter presents explanations on the relevant quantification methods underlying carbon storage and carbon substitution potentials of HWP, current and future carbon storage potentials of HWP under different scenarios according to regional, national and EU-wide scenarios and a review of substitution potentials of HWP in a variety of wood-based products. Furthermore, methodological boundaries and uncertainties when assessing storage and substitution potential are highlighted and a synthesis towards possible ways to enhance the climate mitigation measures with HWP are presented.

3.1 Carbon storage in harvested wood products

In managed forests - as described in Chapter 2 - harvesting removes part of the carbon from the ecosystem, and carbon emissions from wood decomposition partly take place outside the forest. As a result, the amount of harvested tree biomass combined with the rate of decomposition of HWP determines the carbon stock in HWP outside the forest ecosystem. This may comprise an important component of the total carbon stock associated with managed forests. Since the amount of harvested timber, as well as the use of harvested timber in various wood products, depends on the type of forest management and on the type and use of wood product, the total amount of carbon stored in HWP is subject to changes associated with forest use and economic activity.

3.1.1 Analysis of carbon storage in harvested wood products

Many studies have been conducted on carbon storage and the climate change mitigation potential of HWP, with varying results. These disparities can be attributed to methodological differences, e.g. whether HWP stock change or CO_2 fluxes from and to the atmosphere associated with HWP are taken into account. Uncertainties in the assessments are related to estimates of HWP activities, analysis boundaries (i.e., whether imports and exports are included) and effects of international trade, conversion factors, as well as assumed half-lives for HWP categories (FAO 2020). Half-lives relate to the quantification of the product life span and their decay rates. They represent the time when half of the products manufactured in a certain year reach the end of their service life. Most studies use default values on half-life parameters provided by IPCC (Rüter et al. 2019), which are affected by possibly large uncertainties due to lack of data in the scientific literature. Further uncertainties arise from unknowns associated with the end-of-life pathways of wood products. Data on different end-of-life pathways — disposal of wood products (e.g., incineration, landfilling), recycling of wood-based materials (e.g., cascade use) or use as fuel at the end of service life — are difficult to gather, but the different pathways influence carbon balances in different ways and are thus a significant source of variability in the GHG impacts of the wood product life cycle (Sathre and O'Connor 2010).

Immediate effects on the carbon pool in HWP are linked to the type and use of the final product, as mitigation benefits from the use of forest products are affected by product life cycles, which determine the duration of carbon storage in wood products and the substitution benefit (Smyth et al. 2017). In general, carbon stocks in HWP can be increased with little impact on net atmospheric emissions by using a higher share of HWP in end uses with long service lives (e.g., in construction), increasing recycling and reuse of retired HWP, and collecting methane produced from decomposing HWP in landfills and using it to generate energy (Lun et al. 2012; Chen et al. 2014; Smyth et al. 2017). Any analysis of the mitigation potential of HWP should not only consider the entire life cycle of a wood product, but also consider the interaction with other mitigation components (e.g., sink in forest biomass, energy and material substitution by wood) to get a full picture of the interdependencies between forests and the forest value chain.

3.1.2 Scenarios of carbon storage in HWP for EU

The "EU reference scenario 2013" (Capros et al. 2013) for the carbon sink in the forest sector until 2050 projects a continuous increase of the sink in the HWP carbon pool (represented by increasing negative emissions), since part of the harvested biomass is processed to final wood products which have a lifespan of several years and store the carbon.[1] According to their scenario, an increasing demand of wood is projected, driven by population and income growth as well as increasing wood demand for renewable energy production (Figure 5). The scenario sees a significant decline in the managed forests carbon sink and argues that this can be compensated for to a certain degree by an increasing carbon storage in HWP, next to a rising carbon sink from afforestation and a decrease in deforestation.

[1] Note that the EU Reference Scenario assumes that the HWP pool was in steady state in 2000.

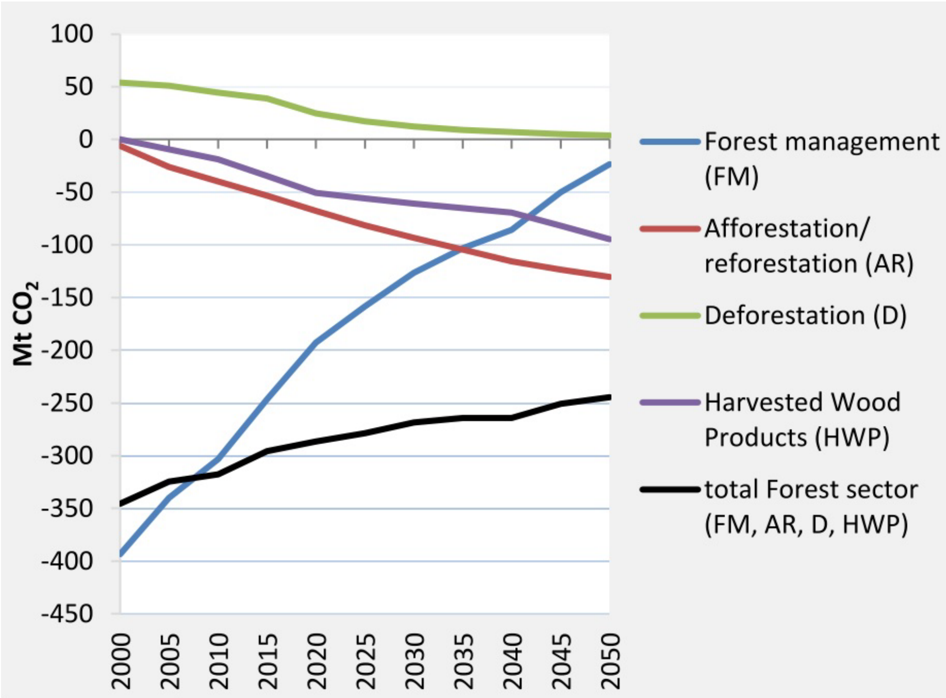

Figure 5. Development of the EU-28 carbon sink in the forest sector until 2050. Note: Negative values describe a carbon sink and positive values a carbon source) (Capros et al. 2013).

Pilli et al. (2015) estimated the emissions and removals associated with HWP for a historical period (1992-2012) and for future scenarios until 2030 for the EU[2], using FAOSTAT data on the production of forest products. The future scenarios analysed the effects of different harvest amounts on the carbon pool of HWP via three scenarios: a constant historical average (i) and harvest amounts that were 20% higher (ii), or lower (iii) than the historical average respectively. Their results show that the average historical HWP sink from 2000 to 2012 was −44.7 Mt CO_2/year, which is about 10% of the sink contained in EU forest pools and nearly 1% of the total EU GHG emissions in the same period.

Figure 6 shows historical and the future HWP sinks estimated, for each scenario. The fact that within the constant harvest scenario the future HWP sink is reduced to −22.9 Mt CO_2/year, (i.e., -49%) in 2030 is interpreted as the result of a "saturation" trend in the HWP pool, as the difference between the inflow and outflow tends to balance out over time and approach an equilibrium if the HWP-pool is not enlarged.

In the increasing harvest scenario, the final HWP sink in 2030 (−43.2 Mt CO_2/year) is almost equal to the historical average HWP sink (2000–2012). This can be explained by the fact that the rate of increase of harvest assumed in this scenario is similar to the one observed in the previous period. This means that in order to keep a constant HWP sink, the rate of increase in future harvest (assuming a constant distribution of harvest to the various commodities) should not be lower than the rate of increase observed in the past.

As expected, reducing by 20% the future harvest rate, the 2030 sink decreases to −9.1 Mt CO_2/year in 2030, i.e., −80% compared with the average historical sink. This is due to the cumulative effect of a reduced inflow

[2] With the exception of Malta and Cyprus

to the HWP pool, to the annual decay rate affecting each commodity (i.e., the outflow) and to the quite strong reduction in the domestic production.

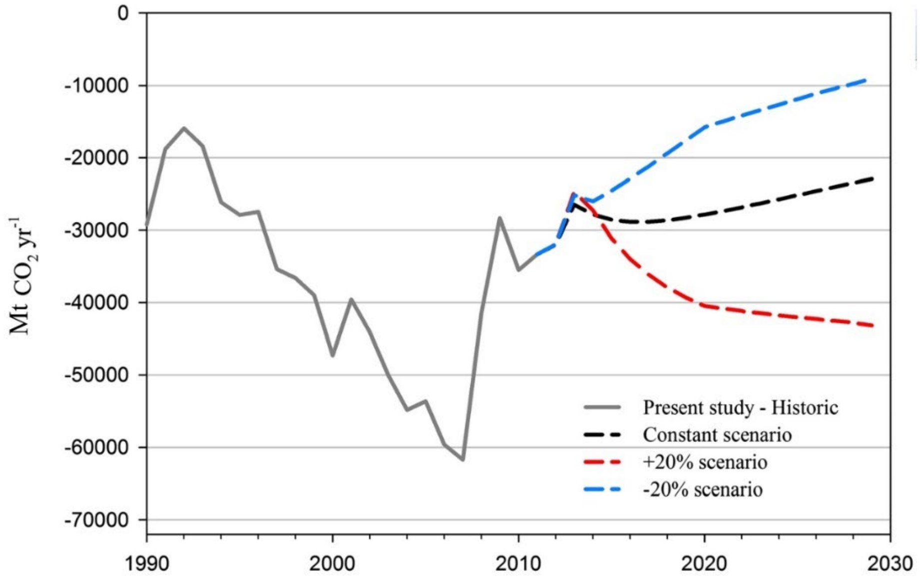

Figure 6. Historical and average future scenarios of carbon storage in HWP (Pilli et al. 2015)

To highlight the effects of different methodological approaches, it is worth noting that even though the higher harvest scenario seems similar to the assumptions made in the EU Reference Scenario, the results for the HWP carbon pool are not comparable due to different methodological assumptions. The main difference is the reference scenario. The EU Reference Scenario assumes that the HWP pool was in a steady state in 2000.

Finally, the scenarios presented by Pilli et al. (2015) do not consider effects on the forest carbon pool. Since forest carbon pool and carbon pool in HWP are tightly linked, both should be considered to get a more holistic picture of potential climate effects of forests and wood products. In general, any reduction in timber harvest or the prolongation of rotation periods respectively lead to an increase in forest carbon pools, while for the HWP carbon pool the opposite is true. An increase in timber harvest and shortening of rotation period commonly leads to an increase in the HWP carbon pool, provided wood product shares remain stable (Bösch et al. 2017). Whether an increase in HWP carbon pool can offset the decrease in forest carbon pool depends on several factors, such as the considered time period, lifetime of HWP, GHG emissions from litter, deadwood and soil organic matter as result of increased timber harvest as well as on the extent of substitution effects of HWP.

Bösch et al. (2017) present five different scenarios, each referring to an alternative level of wood harvests (due to changing rotation lengths or setting forest areas aside), considering effects on forest and HWP carbon pool. Their results suggest that carbon storage in HWP counterbalances sequestration in forests at least to some degree, but that the effects on forest carbon pools usually are stronger than those on HWP pools for the time period considered (2014–2048). Although this study considers the linkage between forest and HWP carbon pools, it does not consider developments in the carbon pool after 2048 and substitution potentials of wood products as contributor to net climate effects.

3.1.3 Summary and outlook of carbon storage potential in HWP

In the future, the current HWP sink can be maintained either by further increasing the current harvest, or by shifting the use of HWP. As it may be difficult to increase carbon sequestration into the HWP pool significantly relative to forest carbon pools (Soimakallio et al. 2016), additional tools to increase the HWP carbon pool, independent from the forest carbon pool offer possibilities towards a more climate effective way to use wood.

These tools include shifting more of the harvest to long-lived products (Smyth et al. 2014; Brunet-Navarro et al. 2017; Nabuurs et al. 2017), rather than the production of short-lived wood products and use for energy of primary biomass. Long-lived products allow the carbon to be stored longer in the HWP carbon pool, whereas the burning of wood that could be otherwise used for materials leads to carbon being released to the atmosphere much faster.

As well as the longevity of wood products, the recycling rate is a determining factor that influences the development of the carbon stock in HWP. The increased rate of production and use of long-lived wood products as well as cascade-use and recycling can increase the HWP carbon pool. Brunet-Navarro et al. (2017) found that the carbon stock in HWP increases linearly when increasing the average lifespan of wood products and exponentially when improving the recycling rate.

Finally, as the examination of climate effects of wood use should ultimately consider all significant fossil GHG emissions to the atmosphere, this should include emissions from raw material transportation. Several national studies hint at relatively increased climate benefits when HWP are produced domestically, since emissions from transportation can be reduced (Paluš et al. 2020; Jasinevičius et al. 2017).

3.2 Harvested wood products and carbon substitution

Together with HWP storing carbon for various periods of time, additional mitigation effects from using wood products can be achieved by reducing GHG emissions from other industrial sectors when wood replaces other, non-renewable materials within the same functional unit (Brunet-Navarro et al. 2017). Such a reduction of GHG emissions as a consequence of product substitution is called a substitution effect.

The substitution benefits of HWP cannot be attributed directly to the forest sector under the current national reporting of GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC), as the emission reductions will be captured in other sectors and potentially in other countries. Nevertheless, information about substitution benefits and potentials is crucial to develop optimal strategies on how forests and the forest-based sector can contribute to climate change mitigation (Leskinen et al. 2018).

3.2.1 Substitution factors

The first step towards assessing net climate effects from substitution is through life cycle assessments (LCA). This tool can be used to compare GHG emissions between different material choices in different product life stages, by assessing GHG emissions during raw material extraction, processing, transportation, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal. The choice of which life cycle stages are included in the LCA and related system boundaries should be clearly stated, as it can have major effects on the overall outcome of the analysis.

Based on LCA, the so-called displacement or substitution factors are calculated as follows (Sathre and O'Connor 2010):

$$SF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}}$$

Where, SF is the substitution factor, $GHG_{non\text{-}wood}$ and GHG_{wood} are the GHG emissions resulting from the use of non-wood and wood options, and WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in wood and non-wood options, respectively.

If the result of the equation is positive, this indicates that using a wood-based product causes less GHG emissions than using the non-wood-based product. So, the substitution factor is a measure of the amount of GHG emission that is avoided when wood is used instead of another material. It is an index, illustrating the efficiency of HWP use reducing net GHG emission and quantifying the amount of emission avoided per unit of wood use (Sathre and O'Connor 2010). Multiplying product volumes by their corresponding substitution factor allows the assessment of the substitution impact of wood-based products at the level of specific market, or sector, such as the construction sector in Europe (Eriksson et al. 2007).

To get a comprehensive evaluation of the substitution potential of HWP all life cycle stages of a product should be considered. The substitution benefits from using wood over alternative non-wood products are largely gained from reduced fossil GHG emissions during the production stage of the wood product. In addition, substantial substitution benefits may also be obtained from energy recovery at the end-of-life stage (Leskinen et al. 2018).

However, it is important to notice that substitution factors alone do not provide sufficient information on the GHG emission balance of HWP. For estimations of the net climate impact, changes in the forest carbon pool and the HWP carbon pool itself need to be considered. Instead, an integral long-term strategic approach, considering long planning horizons and response time in management of forests and developments in wood use is required to formulate the most effective forest and wood management strategies for mitigating climate change (Werner et al. 2010).

3.2.2 Limitations and uncertainties connected to substitution factors

Existing studies and meta-analyses (e.g., Sathre and O'Connor 2010; Leskinen et al. 2018; Myllyviita et al. 2021) indicate that substituting emissions-intensive products by wood products can result in GHG mitigation benefits. Nevertheless, many uncertainties are connected to such analyses, such as:

- the type of wood product being considered
- the type of non-wood product that it substitutes
- the production technologies used
- the different operating life and end-of-life management of wood and non-wood products
- the use of harvest and processing residues

- the quality and quantity of data (e.g., end-of-life pathways of wood products)
- the GHGs considered (only CO_2, or also methane, nitrous oxide, etc.)
- the uncertainty about future product design, technologies and energy supply and future policy instruments
- the methodological choices (e.g., system boundaries, temporal boundaries, allocation of resources).

For the correct interpretation of the substitution factor, one critical step is the definition of system boundaries. As mentioned above, set system boundaries can have major effects on the outcome of substitution factors and also on how they can be interpreted. Substitution factors that describe avoided fossil GHG emissions provide insights on the potential of wood-based products to replace emissions-intensive alternatives, but this is only one aspect of the forests and HWP carbon pools. If substitution factors aim to describe the overall climate effects of wood use, they should include all relevant GHG flows, including an assessment of changes in forest and HWP carbon stock and post-use of HWP (Myllyviita et al. 2021).

Exclusion or lack of data for certain life cycle stages can also influence the outcome of substitution factor calculations. This is especially true for the post-use management of wood products (Sathre and O'Connor 2010). If wood is landfilled at the end of life, methane emissions can contribute significantly to the GHG balance, as it has 28 times the global warming potential compared to CO_2 (Reay et al. 2007). On the other hand, if HWP are recycled or used in energy production, additional benefits can be gained. Furthermore, integrated wood production systems, such as sawmills that produce lumber but which also benefit other sub-sectors of the forest-based bioeconomy (e.g., biochemicals and biofuels) by generating raw materials (e.g., wood chips, bark, sawdust) for these industries, are typically not considered when calculating substitution factors (Leskinen et al. 2018).

The possibility of a cascading use of wood products (i.e., to increase the lifespan using residues and recycled materials) will become more important in the future with the transformation towards a circular economy. Since data on the substitution effects of cascading stages of HWP are rare, it is important to generate new data to be able to measure the impacts of cascading in climate change mitigation, and to explore how this is connected to the substitution factor (Suter et al. 2017).

These future developments indicate that the substitution factor should not be considered static, but rather a dynamic concept that needs to take into account changes over time. Future uncertainties that influence the substitution factor of wood products are also linked to the development of new products and production technologies, as well as the transformation of energy production towards zero emissions (Leskinen et al. 2018; Myllyviita et al. 2021). Since substitution factors will change with a dynamic economic and technological environment, they should be adjusted in future scenario analysis (e.g., Rüter et al. 2016; Hurmekoski et al. 2020).

Lastly, country-specific differences in forest industries, forestry practices, forest growth and structure (e.g., age, tree species proportion) will also cause variations in studies on substitution factors between different countries and regions (Seppälä et al. 2019). As a result, although substitution factors can provide valuable insights into the GHG mitigation potentials of wood-based products, they should not be used on their own to evaluate the climate impacts of forest utilization and for related policy decisions (Leskinen et al. 2018; Myllyviita et al. 2021).

3.3 Estimations of climate change mitigation potential of HWP through substitution

In this section we present the averages and ranges of substitution factors that have been collected from scientific literature for different product and application types. Due to the above-mentioned uncertainties, dependencies and assumptions that surround substitution factors and the fact that constructing averages of substitution factors does not remedy these issues, we emphasize that the values presented are subject to debate and cannot represent the complex reality of actual carbon substitution. Furthermore, average substitution factors are of limited practical use, as they are based on substitution effects reported in the literature and do not consider the extent to which these products are produced or consumed in forest product markets.

Leskinen et al. (2018) performed a review of 488 substitution factors from 64 studies. All reviewed studies that provided information on substitution factors included the production stage of the product life cycle and 40 studies also included the end-of-life stage. A smaller number of studies provided information on the substitution effects of product use and cascading effects.

Across all studies, 91% of the substitution factors that include two or more life cycle stages have a value greater than zero. These findings indicate that wood products generally provide a positive contribution to climate change mitigation at the product level. However, reported substitution factors are subject to large variability due to many different product types, the non-wood materials that are substituted, production technologies, number of life cycle stages considered, and end-of-life management practices.

3.3.1 Construction sector

Building systems represent large wood substitution potentials, as building construction activities largely use non-renewable materials. In addition, about 60% of global raw material use is connected to such activities (Zabalza Bribián et al. 2011). Increasing the use of wood in construction has been seen as an important option and as an efficient way to use biomass to substitute fossil fuels and non-renewable materials. Using wood as a building material affects the carbon balance through at least four mechanisms (Eriksson et al. 2012):

- the relatively low energy inputs needed to manufacture wood products compared with alternative materials
- the avoidance of industrial process carbon emissions from e.g., cement manufacture
- the increased availability of biofuels from biomass by-products that can be used to replace fossil fuels
- the physical storage of carbon.

Three-quarters of the studies reviewed by Leskinen et al. (2018) report on substitution effects focusing on products for the construction sector. The substitution factor derived from these studies generally indicates that, compared to non-wood products, the use of wood for construction purposes results in climate benefits. The substitution factors derived from the literature show substantial variability (Figure 7). The average substitution factor for structural construction is 1.3 kg C/kg C wood product, with 95% of the values ranging between -0.9 kg C/kg C and +5.5 kg C/kg C wood product. The median substitution factor for non-structural construction is 1.6 kg C/kg C wood product, with 95% of the values ranging between +0.2 kg C/kg C and +4.7 kg C/kg C wood product.

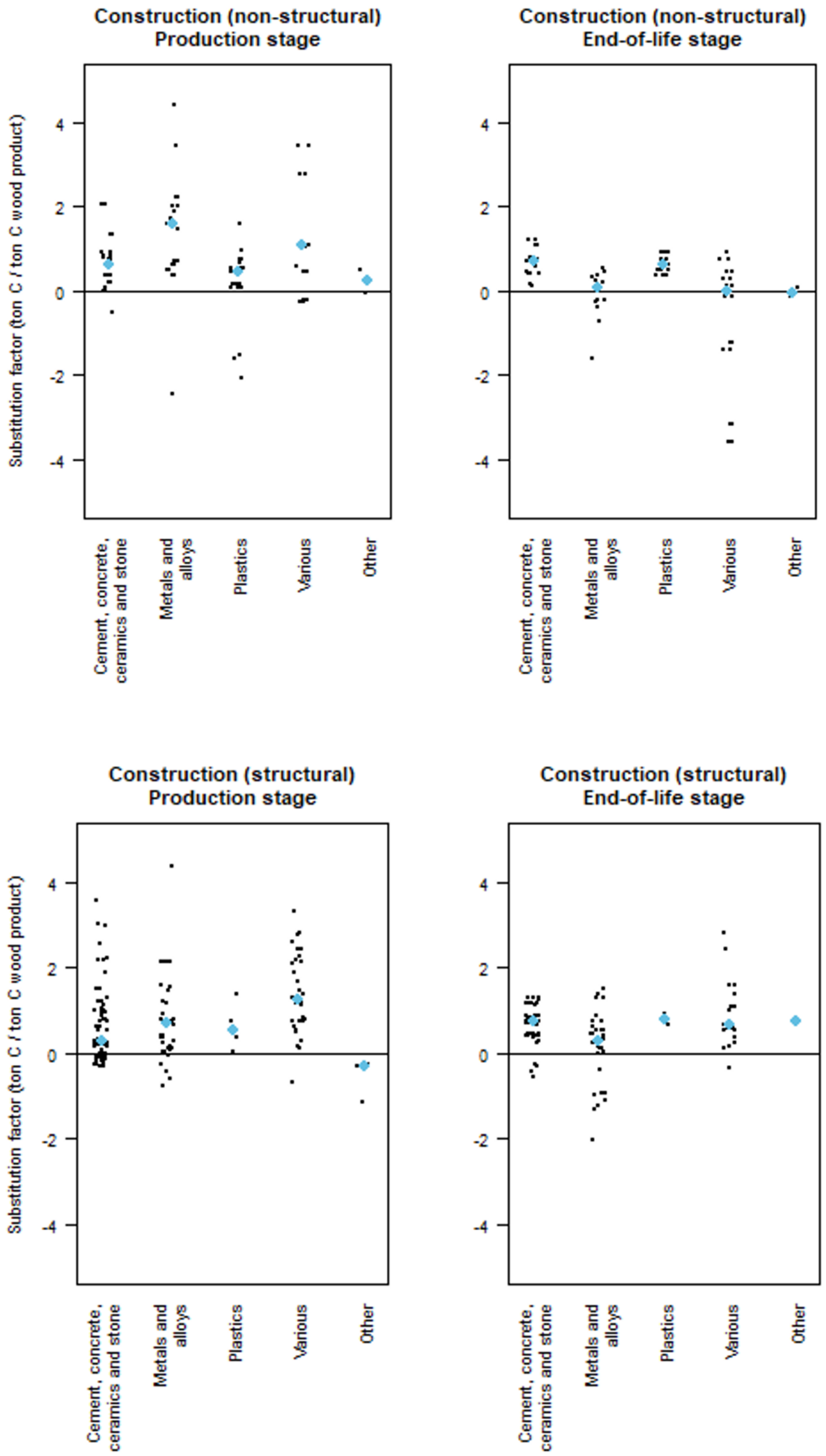

Figure 7. Overview of substitution factors derived for construction products (structural and non-structural) and by life cycle stage (adapted from Leskinen et al. 2018). Note: The black dots indicate individual substitution factors, while the blue dot indicates the median value.

While wood-based construction is still dominated by traditional products such as sawnwood and wood panels, engineered wood products (e.g., cross-laminated timber and glued laminated timber) there is a great potential to substitute fossil-based construction materials like concrete in frames, floors, walls and roofs (Brandner et al. 2016). Due to their more homogeneous technical properties, engineered wood products can directly compete with steel and concrete in some applications and have already been substituted for carbon and energy intensive concrete and steel-based building constructions (Hurmekoski et al. 2018).

Although increasing the use of engineered wood products in the EU can contribute to leveraging a shift towards a more emission-efficient production of construction materials, engineered timber products still lag behind their potential due to market and policy barriers (Churkina et al. 2020; Hildebrandt et al. 2017). The adoption is impeded "by a number of barriers including the resilience of the current technological, and social system, lack of knowledge about applications, lack of financing, insufficient incentives for replacing old technology with new, high costs, and insufficient market demand" (European Environment Agency 2014).

3.3.2 New emerging wood-based products and application opportunities

While the substitution impacts for wood-based products in construction have been relatively well studied, data for other than new and emerging wood-based product applications are still lacking. In addition to construction, promising markets for emerging wood-based products include textiles (Antikainen et al. 2017; FAO 2016), biochemicals, packaging and plastics (Aeschelmann and Carus 2015; Carus et al. 2016). New emerging products offer, next to net climate benefits, the opportunity to increase the value-added from an existing feedstock flow by moving downstream in the existing value chains (Hurmekoski et al. 2018).

The textile industry is one of the world's largest industrial sectors in terms of volume, with rapidly growing global demand driven by increases in population and average income (Antikainen et al. 2017). Two studies (Shen et al. 2010; Rüter et al. 2016) were found that provide data for deriving substitution factors. Based on these two studies, using wood to produce textile fibres may to lead to a substitution effect of 2.8 kg C/kg C (with 95% of the values ranging between 2.5 kg C/kg C and 3.1 kg C/kg C), thereby providing the largest substitution benefits across all assessed product types. As Shen et al. (2010) argue, man-made cellulosic fibers for textiles have better overall environmental and GHG emission impact profiles than the main competing products (e.g., cotton and synthetic fibres). Furthermore, technological developments in the production of wood-based textile fibres aim increasingly for more environmentally friendly methods by promoting a combination of mechanical treatment, reduction of total chemical use and the use of non-toxic chemicals.

The packaging market is driven by global population and GDP growth, as well as increasing e-commerce and demand for take-away products. Together with the constrained supply in the long term, the increasing polymer prices and regulations to ban short-lived plastic products may provide promising substitution potentials for wood-based packaging that can replace plastic packaging (Hurmekoski et al. 2018).

Product categories such as wood-based chemicals, packaging and furniture generally result in moderate substitution benefits with average factors ranging between 1.0 kg C/kg C and 1.5 kg C/kg C of wood product. However, these results are based on only a few studies and are limited to a few product comparisons, which makes it difficult to generalize the results (Leskinen et al. 2018).

Although these emerging wood-based products may only represent a small share in the current markets, they have large substitution potentials. For Finland, substitution benefits could be increased by almost 74% in 2056 at current levels of roundwood removals for industry and energy by altering the market structure. This requires the increasing use of by-products for textiles and wood-plastic composites in place of biofuel, since they provide greater overall substitution benefits (Hurmekoski et al. 2020).

Although the use of wood is expected to increase in the future towards a net-zero economy, for example in construction, textiles, packaging, chemicals and biofuels and construction, there is still a lack of data on and knowledge of climate impacts of emerging forest products (Hurmekoski et al. 2018). However, boosting wood-based construction, leading to increased consumption and production of solid wood products could also benefit other sub-sectors producing biochemicals and biofuels-based and wood-based textiles, by generating raw materials (i.e. wood chips, bark, sawdust) for these industries (Jonsson et al. 2021). A prerequisite towards the increased material use of by-products of sawmilling industry is that the operating energy for sawmills would be produced by other means, or reduced by increased energy efficiency (Stern et al. 2015).

3.3.3 Energy substitution

Table 1 shows substitution factors from scientific studies for the use of forest biomass substituting fossil-based energy. The review presented in this table is not exhaustive, but it aims to show different ranges according to selected studies. It must be considered that the diversity in system boundaries, baseline scenarios, study period, geographical scope, forest management regime, substituted fossil energy source and biomass feedstock source lead to differences wood bioenergy substitution effects.

Despite these constraints, scientific studies in general indicate climate mitigation benefits with energy applications of wood biomass. According to the presented literature, substituting coal shows larger substitution benefits than those from oil and natural gas. Energy recovery from post-consumer wood and the use of harvest residues for energy purposes are found to provide climate benefits relative to fossil fuel burning, with post-consumer wood and recycled paper products showing larger mitigation effects.

The lowest substitution benefit according to the reviewed literature occurs when sawnwood and industrial roundwood is used to substitute for fossil fuels for heating. Although this result was based on a single study, the practice of using sawnwood and industrial roundwood for energy purposes is not advisable, since these assortments and products can be used to produce materials with a long product life (e.g., construction materials and furniture) and incinerated at their end-of-life stage, maximizing climate benefits through carbon storage, product substitution and potentially cascade use throughout their material use.

Also, Geng et al. (2017) point out that time delays to achieve net emission reduction by substituting fossil fuels through bioenergy occur, depending on the type of biomass used for energy generation. “The time required to obtain net emission reduction for wood bioenergy in place of fossil fuels can be zero year (harvest residues that would otherwise be burnt on site), decades or more than a century (standing living trees for bioenergy), depending on forest biomass sources and fossil fuels displaced” (Geng et al. 2017, p. 192).

Table 1. Ranges and values of substitution factors from selected scientific studies

Forest-based material	Substituted fossil-based energy source	Range of substitution factors (t C/t C)	Country	Reference
Forest biomass	Fossil fuel	0.55 (*) - 0.79	Canada	Chen et al. (2018)
			Finland	Hurmekoski et al. (2020) Heinonen et al. (2017)
Forest biomass	Coal	0.8 - 1.27	Germany	Böttcher et al. (2012)
			Sweden	Cintas et al. (2016)
			China	Ji et al. (2016)
Forest biomass	Oil	0.6 - 0.79	Germany	Böttcher et al. (2012)
			Germany	Rüter (2011)
			China	Ji et al. (2016)
Forest biomass	Natural gas	0.4 - 0.56	Germany	Böttcher et al. (2012)
			Sweden	Cintas et al. (2016)
			China	Ji et al. (2016)
Wood-based transport fuel	Fossil transport fuel	0.67 - 0.7	Finland	Hurmekoski et al. (2020)
Harvest residues	Coal	0.47 - 0.89	Canada	Smyth et al. (2017)
	Fossil fuel	0.38 - 0.95	Canada	Smyth et al. (2018)
Post-consumer wood	Fossil fuel	0.98	Finland	Soimakallio et al. (2016)
Paper products (recycled)		0.8	Finland	Soimakallio et al. (2016)
Sawnwood and industrial roundwood	Fossil fuels for heating	0.34 (*)	South Korea	Han et al. (2016)
Wood pellets	Fossil fuel	0.56 (*)	France	Fortin et al. (2012)

** The original unit of substitution factors has been converted to t C/t C using the following values: roundwood density 0.45 t/m^3; carbon fraction of wood 0.5 kg C/kg dry matter; CO_2 conversion of 3.67 kg CO_2/t C*

3.4 Summary and outlook of substitution potential of wood products

Usually wood and wood-based products have lower fossil and process-based GHG emissions when compared to non-wood products. Substitution is the replacement of non-renewable materials and energy with wood, offering potentials to mitigate net emissions. Substitution factors help quantify the difference between the GHG emissions resulting from the use of wood and a predominantly non-wood alternative, relative to the amounts of wood used in the wood product and non-wood product (Leskinen et al. 2018).

The overall substitution benefits depend not only on the relative difference in emissions between two alternative products, but also on the scale of production and consumption of products. To maximize substitution benefits, it is important to focus on fossil-intensive products or fossil energy sectors, that cannot move quickly towards GHG reduction and sectors with large, unexploited market potentials for wood-based products like textiles and plastics and construction.

Next to many uncertainties and methodological differences in assessing substitution factors, it is important to note that substitution factors are not static, but dynamic and change over time with a changing economic and technical environment. Substitution benefits from wood products can even be assumed to decline in the future, as energy sector emissions and consequently emissions from energy intensive industries decline as renewable energy production rises (e.g., Peñaloza et al. 2018). Furthermore, research, especially on climate impacts of new emerging wood-based products, as well as effects of cascade use and end-of-life wood management is needed for more precise substitution factors.

When examining the role of wood-based products in climate mitigation, a holistic approach is essential. Substitution factors are one necessary, but not sufficient, piece of information needed to inform policies. Other factors, such as forest carbon sinks, forest soil carbon sink, and HWP carbon storage need to be considered as well to get a comprehensive assessment of net climate effects of wood use (Leskinen et al. 2018).

Using wood for energy substitution is a politically charged topic. If current harvest levels are increased to produce more bioenergy, carbon that would have been stored in the biosphere would be instead released in the atmosphere. However, studies show that the emissions from the use of bioenergy compared to fossil fuels are time-dependent (Zanchi et al. 2012; Geng et al. 2017). While these studies show that all sources of woody bioenergy from sustainably managed forests will eventually produce emission reductions in the long term, different woody biomass sources have various impacts in the short-to-medium term.

Burning forest residues, post-consumer wood and by-products from the wood industry that have little use for material purposes for substituting fossil-based energy is generally considered beneficial from an emissions perspective. A risk of short-to-medium term negative impacts can emerge when additional fellings are extracted to produce bioenergy or when land with high carbon stocks is converted to low productivity bioenergy plantations (Zanchi et al. 2012).

Furthermore, a recent study on “EU biomass use in a net zero economy” (Material Economics 2021) suggests that:

- Wood products, paper and board, chemicals and novel materials will be particularly high-value areas for future biomass use.
- Many traditional bioenergy applications are set to become increasingly costly compared to new options based on electrification and hydrogen.
- Future high value uses of bioenergy are found in highly specialised uses within industrial heat, power systems and aviation.

This study suggests a course correction away from bulk use of biomass for energy, towards several applications where its unique attributes are effectively deployed and focus on material applications, which typically have the highest value in a net-zero context.

In conclusion, due to the changing economic and technical environment, an integral long-term strategic approach is required to formulate the most effective forest and wood management strategies. This integral approach should evaluate the GHG impacts of various forest management and wood use scenarios under varying economic developments (Werner et al. 2010). Climate Smart Forestry, as introduced in the next chapter, can offer such an integral approach.

4. Connecting the dots through Climate-Smart Forestry

Climate-Smart Forestry (CSF) is an integral approach of sustainable forest management that focuses on forest management in response to climate change (Bowditch et al. 2020). The fundamental focus of the CSF concept is on adaptation, mitigation and social dimensions, which recognizes the need to avoid development of these aspects in isolation. CSF is being interpreted in a number of ways, which mostly focus on adaptive forest management, the decrease of GHG emissions, and effective carbon sequestration (Nabuurs et al. 2018; Yousefpour et al. 2018). Nabuurs et al. (2018) presented the following three pillars of the CSF approach:

- active forest management aiming to sustainably increase productivity and provide all benefits that forests can provide
- adapting forest management to build resilient forests
- reducing and/or removing GHG emissions to mitigate climate change.

The concept of CSF goes beyond forest management measures, including GHG mitigation opportunities of wood use, carbon storage and substitution (Verkerk et al. 2020) in its targets:

- increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services
- using wood resources sustainably to substitute non-renewable, carbon-intensive materials
- enhancing health and resilience through adaptive forest management.

These components aim to increase the total forest area and avoid deforestation, connecting mitigation with adaption measures to enhance the resilience of forest resources, and using wood for products that store carbon and substitute emission-intensive fossil and non-renewable products and materials. The integral nature of the CSF concept acknowledges all carbon pools and integrates forest management and wood use strategies to maximise mitigation benefits.

As discussed in previous chapters, several studies (e.g., Jonsson et al. 2021; Gustavsson et al. 2021; Soimakallio et al. 2021) report mixed results about the impact of increasing or reducing landscape-level harvest rates on the net GHG balance. Therefore, a holistic perspective is needed for developing a framework that considers the multifunctional nature of forests. Firstly, it should be considered that forest growth declines in aging forests, which leads to diminishing removals of CO_2 from the atmosphere (Nabuurs et al. 2013). Secondly, many existing climate impact studies suggest an increasing risk from abiotic and biotic disturbances (Seidl et al. 2017). A strategy focusing on carbon storage in forests may therefore not lead to the intended outcome (Seidl et al. 2014). Thirdly, besides harvesting wood, active forest management allows for quicker and more controlled adaptation of forests to climate change (e.g., selection of tree species and provenances) to ensure resilience of forest ecosystems (Schoene and Bernier 2012). Lastly, using wood sustainably for long-lived products that can substitute non-renewable, carbon-intensive materials, can help to decarbonize the global economy.

While net GHG benefits could, in some cases, be increased in the short term by lowering harvest rates, long-term net climate benefits could be even higher if forest stands that are susceptible to disturbances could be replaced at an earlier point (Gustavsson et al. 2021; Nabuurs et al. 2018). Successful CSF strategies need to balance short- and long-term GHG emission goals, as well as balancing the need for wood production, the protection of biodiversity, health and vitality and the provision of other important ecosystem and social services in a dynamic environment (Verkerk et al. 2020; Bowditch et al. 2020).

CSF measures can be regionally very different due to significantly varying regional circumstances across Europe. A ‘one size fits all’ solution across Europe will not work. However, the use of locally adapted CSF measures, as indicated by several case studies conducted across Europe, can result in overall long-term emissions benefits or more stable forest conditions, better adapted to climate change (see Nabuurs et al., 2018).

Finally, CSF offers a holistic approach, reconciling and aligning mitigation, adaptation needs as well as maintaining or enhancing biodiversity and ecosystem services to guarantee resilient forests and a positive contribution towards GHG emission mitigation today and in the future. Being an integral approach, CSF aims at the balanced implementation of these aspects and avoids isolated approaches that might lead to trade-offs in some of these aspects. It is important to note, that CSF not only entails forest management options, but ultimately also a more efficient use of wood is needed, using the most promising substitution potentials to maximise the positive climate impact that forests and the forest value-chain provide sustainably.

5. Concluding remarks

Consideration of all GHG flows to and from the atmosphere related to forest use is necessary in order to define credible policy and management strategies for mitigating climate change. In addition to carbon sequestration and storage, forests provide a wide range of benefits to society, and the maintenance and improvement of these functions is a fundamental part of sustainable forest management.

The carbon balance of forest landscapes is affected by many factors, including changes in the intensity of biomass harvest. Increased harvesting intensity of forests generally reduces the amount of carbon stored in forest biomass. A decrease in forest carbon caused by additional harvest may lead to an increase in atmospheric carbon concentrations – depending on the counterfactual development of forests if harvest would not have occurred, as well as on storage and substitution effects through the use of wood products. Short-lived wood products and uses which provide a minor substitution benefit (e.g., energy) generally provide small or no benefit to climate change mitigation. However, long-lived wood products can store carbon for decades to centuries. Furthermore, using wood-based products to substitute high-emission intensity alternatives could yield significant climate benefits; however, technological change could reduce the emission intensity of competing products, which would reduce the substitution factors. Comprehensive analyses which consider all aspects of forest use should be used to weight the trade-offs between different strategies and aim to reduce the amount of fossil fuel that is extracted.

As well as carbon sequestration and storage, forests are of key importance to biodiversity and provide a wide range of benefits to society, and the maintenance and improvement of these functions is a fundamental part of sustainable forest management. The contributions of forestry and the forest sector towards mitigating climate change could be optimized with the following key recommendations:

1. Biomass growth, and consequently carbon sequestration, in managed forests should be stimulated through sustainable forest management practices (such as tree species and provenance selection, thinning and harvest regimes), strengthening the resilience of forests to climate change (e.g., by increasing species diversity), and taking into account biodiversity conservation as well as the long-term preservation of soil and water quality.
2. Forest harvesting and carbon storage should be analyzed in conjunction with the other functions that forests fulfill. Reducing wood harvest increases carbon storage in forest ecosystems in the short term, and may bring benefits to biodiversity, soil and water quality. However, it may compromise economic benefits from forests, and the increase of carbon storage is valid until the carbon sink saturates in the forest. In addition, forest management should also consider that natural disturbances such as storms, wildfires and pests are expected to increase under climate change conditions, having immediate economic impact regarding wood applications, and eventually leading to carbon release to the atmosphere.
3. The harvested wood should follow the principles of cascade use. In this approach, wood is used, reused and recycled as long as possible, thereby extending the material's lifetime within the system. In addition, wood should be used for products that store carbon for as long as possible, and for products that provide large substitution benefits by avoiding emissions.
4. Forest-based bioenergy has a role in the transition of the energy sector towards emissions-free energy production. When using woody biomass for energy purposes, preference should be given to post-consumer wood and forest residues that are not suitable for the production of other materials and which do not lead to additional harvest.

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Appendix

Table A1. Impact of changed harvest rates on forest carbon stocks for selected studies

Study	Region	Time horizon	Scenario compared with reference	Change in harvest (Mt CO_2/year)	Change in forest C stock (Mt CO_2/year)	Relevant assumptions
Bösch et al. (2017)	Germany	2048	Scenario 1 Scenario 2	-6.9 6.9	10.3 -14	Reference scenario represents the current and expected economic and legislative framework. Scenario 1 reflects a situation where final felling is delayed with approximately 20 years. Scenario 2 describes the situation after reducing rotation lengths with 17 years on average.
Gustavsson et al. (2017)	Sweden	2040 2110 2040 2110	Production Set-aside	2.5 4 -14.5 -15.5	-4.7 16.4 -22 -7.1	Reference scenario reflects harvesting at the same level as growth using current management practices. In the Production scenario, Pinus sylvestris was replaced by the faster growing Pinus contorta in 50% of the cases and the number of fertilized hectares was doubled. Set-aside assumes that the protected area is doubled.
Jevšenak et al. (2020)	Slovenia	2050	Plan Low High Haz	1.19 -0.48 2.14 1.59	-0.17 2.69 -1.91 -1.18	The reference scenario is based on historical harvest rates, and the harvest rate increases 1% per year in the period 2030-2050. The plan scenario reflects harvesting that is in line with current forest management plans. The harvest rate in the low harvesting scenario is 40 % lower than in the plan scenario. The harvest rate in the high harvesting scenario is increased approximately by 30% compared to the plan scenario. The Haz scenario was based on the plan scenario, but includes four extraordinary natural disturbances appearing in intervals of about 10 years.
Seppälä et al. (2019)	Finland	2050 2120 2050 2120	INT 1 INT 2	6.7 6.7 13.9 13.9	-15.2 -16.3 -32.3 -40.7	Reference reflects the realization of the cutting target of 58 Mm3 per year. In INT 1, the target is increased to 67.2 Mm^3 per year. INT 2 reflects the realization of a cutting target of 77 Mm^3 per year.
Gusti et al. (2020)	EU Central-East EU Central-West EU Northern EU Southern	2030	CP1	0.11 -0.47 -0.97 -0.54	6 3 3 3	The reference scenario reflects a standard forest management model in G4M. The CP1 scenario aims to match the harvest levels estimated for the Forest Reference Levels based on the period 2000-2009, using an alternative forest management model. The production model assigned clearcut and shelterwood logging for all suitable areas, and selective logging for remaining areas.
Jandl et al. (2018)	Austria	2050	1a 1b 1c 2	2.61 1.23 0.51 -11.38	-1.77 -0.79 -0.43 8.73	Reference scenario reflects the implementation of the National Renewable Action Plan 2010, and the annual cuttings increase from 2010-2020. 1a reflects the increase in demand of fuel wood. Management intensification takes place as more thinnings and shorter rotation periods. 1b reflects an increased demand for wood and wood products, with moderate imports. 1c relies on the same assumptions as in 1b, but with increases in timber imports. Scenario 2 is characterized by extensification of harvest by reducing harvest rates and increasing the protected area.