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Chapter 8
Climate-Change Mitigation in the Forest-Based Sector: A Holistic View

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Abstract Forests and wood use can contribute to climate-change mitigation by enhancing carbon sinks through afforestation, reforestation and improved forest management, by maintaining carbon stocks through natural or anthropogenic disturbance prevention, by increasing offsite carbon stocks, and through material and energy substitution by changing the industry production structure and enhancing resource efficiency. As forests grow fairly slowly in Europe, increasing the wood harvesting intensity decreases the carbon stocks in aboveground biomass, at least in the short to medium term (0–50 years) compared to a baseline harvest regime. The key issue is the time frame in which the decreased carbon stock in forests can be compensated for by improved forest growth resulting from improved forest management and the benefits related to wood utilisation. Thus, there is a need to address potential trade-offs between the short- to medium-term and the long-term (50$^+$ years) net emissions. An optimal strategy needs to be tailored based also on regional specificities related to, for example, local climatic and site conditions, the state of the forests, the institutional setting and the industry structures. This chapter presents a way to assess the effectiveness of forest-sector climate-change mitigation strategies across different contexts and time horizons, combining the climate impacts of forests and the wood utilisation of the technosphere. We identify potential 'no-regret' mitigation pathways with minimum trade-offs, and conclude with the research and policy implications.

Keywords Carbon sink · Climate-change mitigation · Counterfactual sceanrio · Forest sector · Net greenhouse gas emissions · Substitution impacts · Time dynamics

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8.1 Introduction

This chapter contains a synthesis of the insights in Chap. 6, dealing with forests, and Chap. 7, focusing on the technosphere. In this chapter, we adhere to the principle of '*what the atmosphere sees*' regarding climate change. What we mean by this refers to two aspects. Firstly, it is necessary to pay equal attention to all factors affecting the climate impacts of the forest sector; that is, to simultaneously analyse a biological ecosystem (forests), a technological system (industries) and a socioeconomic system (markets). This is imperative for the designing and monitoring of climate-change mitigation measures that ensure a *net* reduction in the atmospheric greenhouse gas (GHG) concentrations in a desired time period.

Secondly, the principle of 'what the atmosphere sees' can also refer to the *absolute GHG emissions and sinks*, in contrast to GHG emissions and sinks based on an *accounting framework* used for monitoring and policy purposes. The accounting of GHG emissions and sinks reported under national GHG inventories facilitates tracking of the impacts of mitigation measures, for example, by comparing annually reported values against a baseline. In the EU climate policy framework, forests and forest bioenergy are regulated under the *land use, land-use change and forestry (LULUCF) sector*, for example. Changes in carbon stocks in existing forests are compared with *forest reference levels*—that is, the level of carbon sink tied to the forest management regime of a historical reference period. Although the current LULUCF regulation (EU 2018) contains several flexibilities, the principle is that, if the sinks in managed forests decline below the reference level, in the accounting framework, these emissions need to be reduced elsewhere in the LULUCF sector, or in other sectors outside the EU emissions trading scheme. Thus, the LULUCF regulation aims to make the forest and land- use sector comparable to all other economic sectors in the EU climate policy, thereby emphasising the importance of short-term mitigation outcomes over the possible long-term benefits of wood use. Such accounting principles are a result of international policy processes that emphasise the short and medium term in climate-change mitigation. In this chapter, we refer to comparisons against a reference scenario (synonymous with a counterfactual scenario) to facilitate the drawing of policy implications based on the effectiveness of selected mitigation measures, but this should not be confused with internationally negotiated GHG accounting principles.

The mitigation potential of the forest-based sector can be realised through several alternative measures (e.g. Nabuurs et al. 2017a, b; St-Laurent et al. 2018; Intergovernmental Panel on Climate Change [IPCC] 2019), as summarised in Table 8.1. There is, however, an important caveat—some of the forest-based climate-change mitigation strategies are more effective on short-term climate impacts, whereas others are better for long-term impacts, and also some of the measures may be better suited for one particular regional context than another. Thus, there can be trade-offs between the measures. Moreover, in real life, forests are used for multiple purposes simultaneously, leading to mixed climate-change mitigation strategies that consider the balancing of different societal objectives and needs for forests.

Table 8.1 Selected climate-change mitigation measures related to forests and wood utilisation

Category	Type and timing of impact	Example and description
1A Increase forest area	Enhance sink: delayed impact	Afforestation and reforestation enhance forest carbon sinks
1B Maintain forest area	Reduce source: immediate impact	Avoid land-use change: reducing deforestation prevents biogenic emissions from occurring
2A Increase site- level carbon density	Enhance sink: delayed impact	Improve forest management: increasing the growth rate of forests and forest carbon sinks by, for example, using improved regeneration materials (seeds and seedlings) or forest fertilisation
2B Maintain site- level carbon density	Reduce source: immediate impact	Avoid forest degradation: for example, protect old-growth forests to maintain forest carbon stocks and promote forest conservation (and biodiversity)
3A Increase landscape-level carbon stocks	Enhance sink: delayed impact	Apply principles of sustainable forest management: enhancing forest carbon sequestration (growth) and maintaining higher stocking in thinning (possibly also longer rotations), while provisioning other ecosystem services
3B Maintain landscape-level carbon stocks	Reduce source: immediate impact	Increase forest resilience to natural disturbances: adaptation of forests and forest management to climate change, for example, by increasing the species diversity in forest stands, and forest resilience to different abiotic and biotic damage by various means (see Chap. 3)
4A Increase offsite carbon in wood products	Enhance sink: immediate impact (if meeting also 1B, 2B and 3B)	Increase the share of long-lived wood products: increasing the share of, for example, construction products in the overall wood-industry product portfolio to increase carbon storage outside the atmosphere, irrespective of the amount of wood harvested
4B Increase material and energy substitution	Reduce source: immediate impact (if meeting also 1B, 2B and 3B)	Increase the share of low-emission wood products: increasing the share of, for example, textiles in the overall wood-industry product portfolio to avoid fossil emissions, irrespective of the amount of wood harvested; increasing material efficiency and clean, non-burning energy in wood-based product chains to avoid fossil emissions through the reallocation of sidestreams

Modified after Nabuurs et al. (2007, Fig. 9.4). Note that the impacts of any strategy need to be assessed on a case-by-case basis, and in a comprehensive framework, in order to avoid oversimplified conclusions

As a rule, in terms of climate-change mitigation, increasing wood harvesting intensity decreases carbon stocks in forests compared to the baseline harvest, at least in the short to medium term (see Sect. 8.3). Thus, the effectiveness of a mitigation strategy depends on the *net emissions* (expressed as CO_2 equivalents) over time—the reduction in the carbon sink caused by harvesting, and the time by which the reduction is compensated for by the recovered forest carbon stock, the avoided fossil emissions and the carbon stored in products. How do we analyse the effectiveness of these strategies across different contexts?

8.2 Estimating the Impacts of Mitigation Strategies

Creating an understanding of the overall climate impact of the forest-based sector requires simultaneous consideration of carbon stock changes in standing trees, soil and harvested-wood products (HWPs), as well as the avoided fossil emissions from the substitution impacts of wood use. The forest carbon sink equalled −373.5 $MtCO_2eq$/year and the HWP sink equalled −40.6 $MtCO_2eq$/year in 2017 (European Economic Area [EEA] 2019). There are very few systematic estimates for substitution impacts, but according to Holmgren (2020), the material and energy substitution impact of wood use in Europe in 2018 accounted for −410 $MtCO_2eq$/year. For comparison, the total European GHG emissions (without the LULUCF sector) were 4333 $MtCO_2eq$/year in 2017 (EEA 2019). Note that in GHG inventories, negative values stand for removals from the atmosphere and positive values stand for emissions to the atmosphere. Note also that the estimate of overall substitution impacts refers to the amount of avoided fossil emissions compared to a hypothetical situation in which no wood would be used, and cannot therefore be directly compared to the absolute forest and HWP sink impacts that portray the changes in carbon stocks from one year to the next. Thus, adding the above individual impacts together (forest carbon sink, HWP sink, substitution) would provide no direct or necessarily meaningful interpretation without a comparison to a common reference.

In the context of climate-change mitigation, it is therefore essential to differentiate between the *current emissions balance* and the *changes in the emissions balance* as a result of mitigation strategies. This requires quantifying at least two scenarios, one with the current portfolio of mitigation actions and one with the new portfolio of mitigation actions. The difference between these two scenarios reveals the climate impacts of a new mitigation strategy relative to the current one. For this reason, the most important step in analysing the climate impacts of wood use is to compare the mitigation outcomes against a *counterfactual scenario* through time. Essentially, the counterfactual scenario determines how GHG emissions caused by wood utilisation would have developed over time, if the forest management and wood-use regime had not been subject to the selected set of climate-change mitigation strategies. For example, one could examine the difference in net GHG emissions over a 50-year period, if wood harvesting in the EU was increased by 15% compared to maintaining the current harvest level. Varying approaches have been used for this type of analysis. A useful starting point can be to compare alternative scenarios to a counterfactual scenario, determined as a reference or business-as-usual scenario, in which the sector would develop according to past trends or according to the most recent forecasts.

The difference in GHG emissions between baseline Scenario *b* and alternative Scenario *a* in time interval [*t0, T*] can be calculated according to the following equation (Seppälä et al. 2019):

$$\Delta NGHGE_{b-a} = \int_{t_0}^{T} (TC_b(t) - TC_a(t) + SC_b(t) - SC_a(t) + PC_b(t) - PC_a(t) - (SI_b(t) - SI_a(t))dt, \tag{8.1}$$

where *TC* is the tree carbon stock change, *SC* is the soil carbon stock change, *PC* is the product carbon stock change, *SI* represents the substitution impacts, and *t* is the year. If the result of Eq. (8.1) is negative, the mitigation potential of a strategy adopted in Scenario *a* is better than the mitigation potential of Scenario *b* in time interval $[t_0,T]$ (e.g. in the next 30 years). Thus, Eq. (8.1) allows us to compare the different outcomes of selected strategies on the cumulative GHG emissions over a certain time span. However, assessing the most appropriate time interval for interpreting the climate benefits of different wood-utilisation strategies is not straightforward (see Sect. 8.3). In practice, it is useful to assess the climate impacts of strategies both over the short and medium term (0–50 years) and in the long term (50^+ years).

Peer-reviewed landscape-level studies that have determined the net climate impacts of mitigation scenarios against a counterfactual scenario for different harvesting intensities indicate a clear trade-off between short-term and long-term mitigation outcomes (Werner et al. 2010; Lundmark et al. 2014; Smyth et al. 2014; Matsumoto et al. 2016; Soimakallio et al. 2016; Gustavsson et al. 2017; Heinonen et al. 2017; Chen et al. 2018; Pingoud et al. 2018; Valade et al. 2018; Seppälä et al. 2019; Kalliokoski et al. 2020; Jonsson et al. 2021). The climate impacts are affected by the initial age structures of the studied landscapes in interaction with plausible management of the stands over time. For example, the positive effects of increased forest carbon sequestration through higher stocking of growing stock has been found to be greater for the initially young and middle-aged forest landscape, while the total climate impacts remain more sensitive to the substitution impact or timber-use efficiency than to the initial stocking (Baul et al. 2020).

Applying Eq. (8.1) may be difficult in practice, when considering the uncertainties relating to the long-term projections for carbon sinks and substitution impacts, such as the risk of sink reversals due to forest disturbances or changing product portfolios. Besides questions on the accuracy, the utility of the equation in terms of the managerial and policy implications depends on the scope of the factors considered when calculating the outcomes of the scenarios. For example, in the case where there is an anticipated increase in natural disturbances, one could recommend premature final felling to avoid even higher net emissions, whereas a more holistic strategy would additionally consider adaptation measures, such as increasing the tree species diversity of forest stands. Importantly, it is likely that there are at least some indirect, and not easily quantifiable, impacts missing from the calculation, such as carbon leakage, forest management incentives created by forest-owner revenues, and other socioeconomic cascade impacts, which calls for broader assessment and interpretation (e.g. Favero et al. 2020). Nonetheless, without systematic modelling tools and explicit comparisons between scenarios (such as in Eq. (8.1)), the results are not necessarily going to be transparent, and the meaning of the time span may be left without interpretation, or the interpretation may be overly simplistic.

8.3 Time Dynamics of Fossil and Biogenic Emissions

Regarding the comparisons between mitigation and counterfactual scenarios, it is important to understand that the impacts of mitigation strategies in given circumstances will change according to the selected time interval, among other scope considerations (see, e.g., Pingoud et al. 2012). In many studies, however, an interpretation of the results with regard to different time intervals is largely missing.

There are fundamental differences between biogenic and fossil carbon flows, even though the GHG compounds and their impact on the climate are identical. This is because the biogenic carbon in forests can be considered to be in balance between the biosphere and the atmosphere, if the original growth circumstances of the forests continue and the harvesting areas remain as forests. By contrast, fossil emissions disturb the carbon balance by adding carbon from geological stores to the atmosphere. Both carbons are removed from the atmosphere through photosynthesis and emitted to the atmosphere through respiration, decay and fires, but are also stored in plants, in the organic matter in soils and in HWPs.

According to the concept of *carbon neutrality*, the carbon emissions and sinks from a (managed) forest ecosystem are in balance over the long term (e.g. Nabuurs et al. 2017a, b). Therefore, in the long term, the use of biomass feedstock does not result in permanent increases in atmospheric CO_2 concentrations, when sustainably sourced. However, this definition of carbon neutrality should not be confused with what is agreed in the international GHG inventory reporting conventions. Despite the actual unit emissions from biomass burning exceeding those of fossil fuels (Zanchi et al. 2012), biomass burning is reported as zero emissions in the energy sector in order to avoid double counting between the energy sector and the LULUCF sector. This is because the carbon impact is already fully counted in the LULUCF sector as increased net emissions due to a reduction in carbon stocks in forest ecosystems as a result of harvesting wood. Thus, the actual impact of wood use on the net emissions of the economy needs to be assessed case by case, by tracking both the ecosystem and technosystem GHG flows through time. For example, if the average substitution impacts were increased to the extent that they almost offset a temporary decline in the carbon sink (compared to baseline), an increase in harvesting level could be interpreted as resulting in net neutral impacts in the short run, but in net mitigation benefits in the long run because permanent fossil emissions and sink saturation would have been avoided.

Forest biomass harvesting leads to a temporary decline in the forest carbon stock. The time lag for achieving net mitigation benefits through biomass utilisation can be described using two concepts—*carbon debt* and *carbon parity* (Mitchell et al. 2012). The carbon debt repayment period refers to the period between biomass harvesting and the point at which the overall GHG emissions balance of the harvest scenario (including potential avoided fossil emissions through wood utilisation and carbon stock in wood products) offsets the loss of carbon stored in the biomass at the time of harvesting. The concept of carbon parity also takes into account the accumulated ecosystem carbon that could have occurred had the harvest not taken place. This leads to the comparison of a scenario with the defined activities against a scenario without those activities—the counterfactual scenario. The repayment period depends on, for example, the latitude (boreal, temperate or tropical), biomass feedstock source (stemwood or residue), spatial scale (forest stand or landscape), type of fossil fuel replaced (coal, oil or gas) and energy usage (heating or power generation) (Geng et al. 2017), as well as the initial state of the forest, the forest growth rate and the management practices (Valade et al. 2018).

Reviews focused on wood-based bioenergy have determined that the range of parity times proposed in the literature exceeds two centuries (Lamers and Junginger 2013; Bentsen 2017). Bentsen (2017) found that the carbon debt and parity times vary mostly due to the assumptions used, and that methodological rather than ecosystem- and management-related assumptions determine the findings. According to Lamers and Junginger (2013), parity times are primarily influenced by the choice and formulation of the reference scenario and the assumptions relating to fossil-fuel-displacement efficiency. Generally, in the EU forest context, harvesting trees for bioenergy has been estimated to have a parity time exceeding a century for final fellings, less than a century for thinnings, and from a few years to a few decades for forest residues (Nabuurs et al. 2017a, b; Pingoud et al. 2018). In some cases, such as when using forest residues, dead or damaged wood from natural disturbance sites, or new plantations on highly productive or marginal land, the net carbon benefits can be almost immediate (Lamers and Junginger 2013). The parity times have apparently been studied mostly in relation to bioenergy exclusively, so that evidence on the range of parity times that consider all major GHG flows (i.e. including material substitution impacts and HWP carbon sinks) remains limited. In one such assessment for Canada, the parity time ranged from 43 years to more than a century (Chen et al. 2018), depending on counterfactual assumptions. However, as noted by Bentsen (2017), the lack of consensus on carbon debt and parity times among researchers implies that the concept remains inadequate in itself for informing and guiding concrete policy development, with too many of the outcomes and conclusions relying on methodology and assumptions. Nonetheless, in the absence of better metrics, these concepts are helpful in understanding—at least conceptually—the temporal delay in climate benefits relating to an expanding bioeconomy.

Besides the temporal dynamics, it is necessary to note that the spatial scope of the analysis can also influence the conclusions. The broader the spatial context, the more policy-relevant the conclusions become. That is, compared to an analysis at the single forest stand level, an analysis at the landscape level ought to consider a more holistic range of contributing factors and interdependencies, even if this means some detail is lost. Importantly, at the forested landscape level, there is no carbon debt associated with a baseline harvest due to the mixture of stands in different developmental stages that average this out. The landscape-level analysis is also more relevant to analyses at the regional or national levels than the stand-level analysis. Still, it is clear that more carbon could have accumulated in the ecosystem in the short to medium term with a lower harvest level, in the absence of natural disturbances, which is why the carbon parity period needs to be considered at all levels of analysis (Nabuurs et al. 2017a, b).

It has been estimated that global net emissions ought to be reduced at an annual rate of around 7% between 2020 and 2030 to be able to limit global warming to 1.5° (Olhoff and Christensen 2019). This roughly equals the annual net emissions reduction produced in 2020 by the global lockdown measures, which were on an unprecedented scale, resulting from the COVID-19 pandemic (Olhoff and Christensen 2020). This urgency may be in conflict with the carbon parity times of several decades associated with increased wood harvesting, although it has to be recognised that this depends on the counterfactuals that should also account for various market and ecosystem responses, for example, that current models typically ignore (see, e.g., Favero et al. 2020). Nonetheless, due to the potentially existing carbon parity period, it is necessary to track both the biogenic carbon dynamics and the fossil-based production systems over time in order to enable the designation of realistic and sustainable mitigation strategies that will not increase atmospheric carbon within a given time period, and at the same time will allow a rapid run-down of the fossil-based economy.

Importantly, although science can facilitate an understanding of the implications of different time scales, this is not sufficient for judging how the short- and long-term benefits should be appraised against one another, as this requires a value judgement. Such judgements may also get confused in climate policy with the motives of different stakeholder groups, such as the definition of sustainability (i.e. the level of human interference with nature) (Camia et al. 2021). The appraisal of short- and long-term climate-change mitigation measures also depends on the overall mix of mitigation policies and strategies that exist outside the forest sector through time. Thus, there is no conclusive view on what scale and in which time frame a temporary increase in atmospheric carbon can be tolerated in order to yield long-term benefits. For example, the precautionary principle would suggest that a temperature overshoot should be avoided, which might lead to the idea that the level of harvesting should be immediately reduced to promote higher forest carbon sink for the coming decades. However, biological sinks eventually become saturated, and may be prone to natural disturbances, unless managed and continually harvested to meet various human demands, so reducing the harvest level would ultimately cause higher permanent fossil-based emissions (IPCC 2019).

8.4 Viable Strategies for Climate-Change Mitigation in the Forest Sector

It is widely recognised that the forest-based sector can play an important role in climate-change mitigation. However, optimising between the short- and long-term benefits can be tricky (IPCC 2019). An optimal harvesting intensity, from the viewpoint of carbon sinks and the amount of wood utilised, will vary. Due to the complexity of the system, it is not possible to draw a clear line at a level of harvesting that could be characterised as (un)sustainable. Thus, there is clear motivation for seeking ways to reduce the net GHG emissions of the forest-based sector that would not lead to adverse consequences either in the short or the long term. In the following, we explore some examples of how this could be achieved.

Increasing the net carbon-sink capacity of forests can be achieved by simultaneously improving their carbon sequestration while reducing their GHG emissions, for example, in drained peatland forests. Forest fertilisation is the most effective measure for increasing the carbon sequestration of forests in boreal locations in the short term, whereas the use of improved forest regeneration material is an even more effective measure in the long term, but their combined use is the most effective (Heinonen et al. 2018). Also, on organic peatland forest soils, avoiding the unnecessary maintenance of ditches can result in lower decomposition rates in the peat layer and its attendant GHG (especially CO_2) emissions as a result of raising the water table.

According to FAOSTAT data, the EU27's share of world forest area was 3.9% in 2020. At the same time, the EU27's share of world forest industry exports was 40.8% in 2019 (worth US$100 billion). With such an intensive focus on providing forest-based products for global markets, the EU has a major opportunity to steer sustainable production and consumption. Indeed, the substitution impacts and HWP sinks of wood use could be increased without affecting the forest carbon sink via at least three channels. Firstly, by increasing the resource efficiency and reducing the carbon footprint of the current forest products in the entire value-chain relative to the current situation. Secondly, by changing the portfolio of current products. The byproducts of wood-using industries could be increasingly used to produce biochemicals, for example, and to satisfy the operational energy demands of pulp mills and sawmills using alternative (renewable) energy sources or by increasing the energy efficiency of such mills. Thirdly, by innovating new forest-based products with higher substitution impacts than the current forest products, and replacing the latter. Increasing the relative use of wood in the construction, textiles, packaging and chemicals markets in place of, for example, graphic papers would reduce the demand for concrete, steel, cotton, plastic and oil derivatives, and would plausibly result in reduced net emissions, *ceteris paribus*. However, even if the product portfolio could be influenced by strategies or policies, the demand for forest-based products will largely be shaped by consumer preferences, industry competitiveness and the availability of alternative products to satisfy the same needs. Moreover, the impacts of changes in the product portfolio ought to be assessed case by case, and considering the possible indirect impacts. Targeting an increase in the share of long-lived wood products does not guarantee climate benefits in itself, due to the markets adjusting to the changing supply and demand, which may lead to unwanted spillover impacts. However, it may be possible to use industrial byproducts for construction, for example, in the form of concrete additives or walls made of nanocellulose, which might increase both the HWP sink and the substitution impacts compared to the baseline. Finally, markets will also always demand short-lived products, such as packaging, hygiene papers and textiles, and it makes sense to produce these with as low a carbon footprint as possible, which might also mean using wood-based products.

A key aspect for sustainability lies in addressing the overconsumption of natural resources, meaning that the demand for virgin raw materials—in particular, single-use, non-renewable materials—needs to be reduced. Apart from reducing consumption through carbon pricing, for example, this could be achieved by increasing recycling and reuse (circular economy, cascade use), and by increasing the resource efficiency of production (e.g. Böttcher et al. 2012). Increasing circularity (i.e. the cascading use of wood biomass) leads to a longer delay in the release to the atmosphere of the biogenic carbon that is stored in wood-based products, while also reducing the need to harvest virgin biomass. However, an increase in cascading use requires the avoidance of harmful substances in wood-based products, as these could hinder the effective recycling and reuse of these wood materials (European Commission 2018). Thus, eco-design is a key measure for improving the circularity and substitution effects of wood products for the future.

Besides mitigation strategies, it is necessary to simultaneously build forest resilience against the changing climate and increased forest disturbances, notably by moving from monoculture forests to mixed forests (see Chap. 4). This will also require the adaptation of industry production structures to accommodate the changing wood supply. According to Dugan et al. (2018), the most effective forest-sector mitigation measures are likely to be those that retain or enhance the co-benefits and ecosystem services of forests, such as biodiversity, water quality and the economy, in addition to achieving climate-change mitigation benefits. Moreover, the mitigation portfolios need to be regionally differentiated in order to be effective (e.g. Smyth et al. 2020).

8.5 Key Messages

- The climate impact of the forest-based sector value chain, from forestry to the disposal of forest-based products, should be analysed from the point of view of 'what the atmosphere sees'—that is, what is the net GHG impact on the atmosphere of changes in all product stages. The net climate impact of wood use is the sum of complex interactions between net carbon sinks in forests (tree and soil carbon sinks: see Chap. 6) and changes in the GHG emissions of the technosphere (HWP carbon sinks, substitution impacts: see Chap. 7), as well as the biophysical impacts related to forests (albedo, aerosols, black carbon: see Chaps. 3 and 6). The net impacts are influenced by the selected time frame, as well as future assumptions about markets (market structure, leakage effects), forest management regimes, the risks of carbon sink reversals (natural disturbances), etc. All these determinants ought to be assessed against a counterfactual scenario—what would the carbon balance have been if the selected mitigation strategies were not followed?

- It is difficult to simultaneously perceive the impacts of all these factors, not to mention capture their influence in quantitative modelling in a single peer-reviewed article, or even as part of a multidisciplinary research consortium. There is already significant uncertainty around the major components of the net GHG balance, primarily in the outcomes of models predicting the future forest carbon sink and the substitution impacts. Together with alternative system boundaries and widely varying assumptions, this may help us to understand why opinions based on science can differ. We simply do not know for certain what the optimal forest rotation or optimal production structure should be, considering all of the above factors. Because the scope of even state-of-the-art studies is limited, therefore not allowing the direct policy implications to be understood, attention is required when interpreting the results of such studies.
- Depending on the counterfactual, there can be a short-term trade-off between increasing the level of harvesting to increase the substitution impacts and reducing the level of harvesting to increase the net carbon sink. At the same time, all GHG emissions to the atmosphere need to be rapidly reduced, regardless of their origin. Thus, it becomes necessary to explore 'no-regret' strategies for boosting the forest-based bioeconomy. This includes developing new low-carbon innovations in the forest-based bioeconomy, improving the resource efficiency and circularity of the current bioproducts, and ensuring the vitality and resilience of forests against natural disturbances. The effectiveness of management measures also needs to be assessed in their socioeconomic context, paying particular attention to a rapid and just transition away from fossil-based industries. Thus, it becomes necessary to simultaneously consider mitigation and adaptation strategies, along with other societal goals.

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