European Commission

The European Commission's Knowledge Centre for Bioeconomy

Brief on the role of the forest-based bioeconomy in mitigating climate change through carbon storage and material substitution

Key messages

1. Assessing the role of the forest-based bioeconomy in mitigating climate change requires a "system-perspective", considering all possible options: increasing carbon stocks ('net sink') in forest land and in Harvested Wood Products (HWPs), and using wood to substitute other materials or fossil fuels (see section 1).
2. Reducing the harvest appears the easiest option to increase the net forest sink in the short to medium term (2030-2050). However, this option would have negative socio-economic impacts in the forest sector and would likely lead to a net forest sink saturation in the long term (see section 2).
3. Increasing the harvest would make more wood available for carbon storage in HWPs and for material substitution. However, in the short to medium term, the potential additional benefits from HWPs and material substitution are unlikely to compensate for the reduction of the net forest sink associated with the increased harvest (see sections 3 and 4).
4. A further increase in the net annual forest increment, through forest management practices and new forest area, is necessary to reverse the current trend of declining sinks and thus align the contribution of the forest-based bioeconomy with the EU goal of climate neutrality by 2050 (see section 2).
5. Part of this extra increment could also increase the potential for carbon storage in HWPs and for material substitution. A shift towards greater use of wood products with longer service lives and substitution benefits can enhance their climate change mitigation benefit (see sections 3 and 4).
6. A holistic assessment is essential to guide policies that ensure that the forest-based bioeconomy makes an effective and resilient contribution to climate change mitigation. For example, where a future increase in harvest is expected because of age-related dynamics in managed forests or adaptation needs, then using this 'unavoidable' extra harvest for storing carbon in wood products and for material substitution would bring climate benefits compared with a business-as-usual scenario of wood use (see section 5).

1. What are the climate change mitigation options associated with the forest-based bioeconomy?

The forest-based bioeconomy can contribute to the Paris Agreement's aim to achieve a balance between anthropogenic greenhouse gas (GHG) emissions by sources, and removals by sinks[1] (UNFCCC, 2015), by increasing the carbon stocked in forest land and in harvested wood products (HWPs)[2] and by substituting GHG-intensive materials or energy from fossil fuels, thereby avoiding GHG emissions in other sectors.

In recent years (2016-2018), both forest land and HWPs have acted as net carbon sinks in the EU[3], removing on average about -360 Mt CO_{2e}/yr and -40 Mt CO_{2e}/yr, respectively (EEA, 2020) (Figure 1). Thanks to these, the overall Land Use, Land-Use Change and Forestry (LULUCF) sector, which also accounts for the net GHG sources from other land uses (e.g. cropland, grassland, wetlands, settlements), has been a net sink of about -265 Mt CO_{2e}/yr in the period 2016-2018, equal to 7% of total EU GHG emissions. Since 1990, the annual net LULUCF sink has been rather stable, ranging from -250 to -335 Mt CO_{2e}/yr.

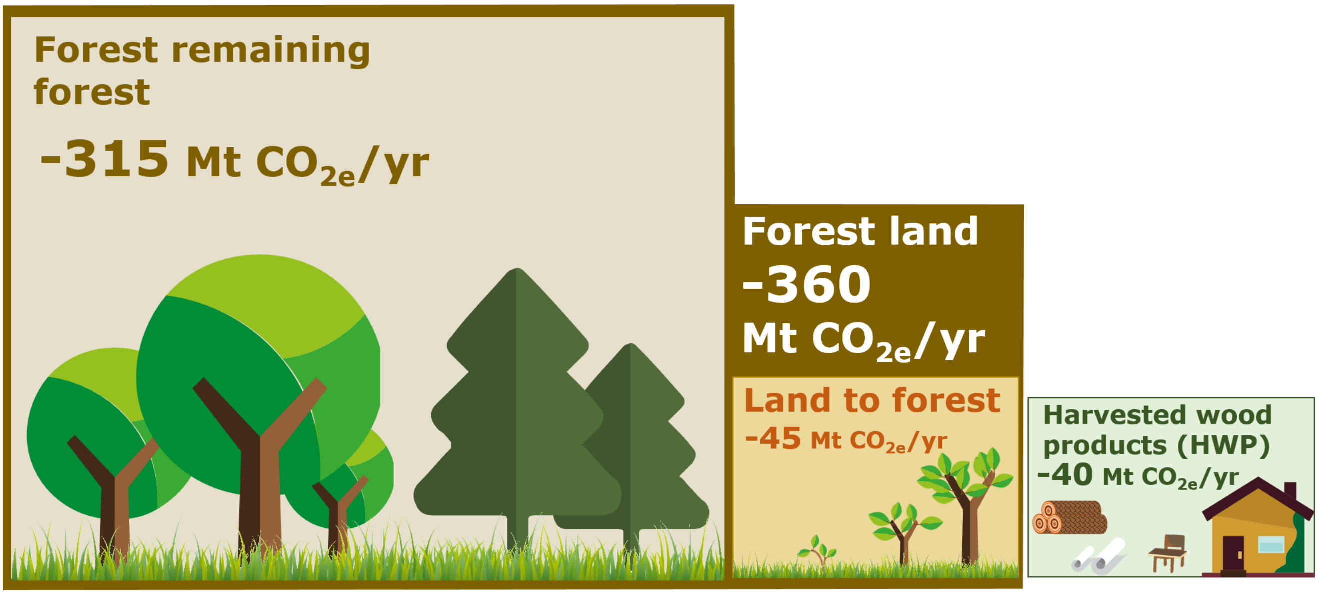

Figure 1. Approximate average net carbon sinks in the EU[3] during the period 2016-2018: forest land (-360 $MtCO_{2e}$/yr) and HWPs (-40 Mt CO_{2e}/yr), together offsetting -400 Mt CO_{2e}/yr, i.e. about 10% of total EU GHG emissions. The net sink from 'forest land' results from the 'forest land remaining forest land' (about -315 $MtCO_{2e}$/yr) and the 'land converted to forest land' over the past 20 years (about -45 Mt CO_{2e}/yr) and include changes in carbon stock in living biomass, dead organic matter and soil organic carbon.

Enabling the EU to become climate neutral by 2050 (EC, 2020a) would require, on top of a drastic decarbonisation of energy, transport, industry and other sectors, that the net sink from LULUCF reaches about -425 $MtCO_{2e}$/yr (EC, 2020b) in order to compensate for the remaining GHG emissions, e.g. from agriculture and some industrial sectors. For forest land, this scenario implies increasing the net sink from the current level of -360 Mt CO_{2e}/yr to -450 Mt CO_{2e}/yr by 2050 (EC, 2020b). The climate mitigation potential in conjunction with other sustainability aspects of using wood to replace GHG-intensive materials and of using wood for energy are attracting increasing attention in scientific and policy discussions.

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[1] A sink is "any process, activity or mechanism which removes a greenhouse gas from the atmosphere" (IPCC, 2019a). More broadly, a given pool can be a 'net sink' for atmospheric carbon if, during a given time interval, more carbon is flowing into it than is flowing out. This is why this brief, for simplicity, refers to the HWP pool acting as a 'net carbon sink', even if it does not remove carbon dioxide from the atmosphere. A decrease in carbon stock, often called 'net carbon source', corresponds to a transfer of carbon to other pools or to the atmosphere.

[2] Harvested Wood Products (HWPs) are wood-based materials (including bark) harvested from forests, that leave the harvest site and are used for products such as furniture, plywood, paper and paper-like products, or for energy (UNECE, 2008).

[3] Throughout this brief, the term 'EU' refers to the 27 Member States of the EU since the departure of the UK on 31 January 2020.

Forests provide many ecosystem services other than wood supply and carbon sequestration (e.g. regulation of the water cycle, protection against erosion, hosting and conservation of biodiversity, provision of cultural and social benefits). At EU level, modern forest management attempts to balance different services while taking into account the existing complex interactions and the needs of society, considering the forest as a "multi-functional" system (SoEF, 2020; Mauser et al., 2021).

Box 1. Accounting forest mitigation actions through the Forest Reference Levels

Regulation 2018/841 (LULUCF Regulation, EU, 2018) sets the current "accounting rules" for the LULUCF sector, i.e. how the GHG fluxes (emissions and removals) from LULUCF will be counted towards the GHG emissions target of -40% by 2030 relative to 1990 (EC, 2014). These rules "filter" the net GHG fluxes reported in the GHG inventories to better reflect the impact of mitigation actions (Grassi et al., 2018). The Regulation requires EU Member States (MS) to balance their accounted GHG emissions in the LULUCF sector by an equal amount of accounted GHG removals. A technically complex aspect of the Regulation is the accounting rules for managed forest land (i.e. forest land remaining forest land), which are based on a Forest Reference Level (FRL) estimated nationally by each MS.

The FRL is a projected benchmark of net GHG fluxes from managed forest land, against which future net GHG fluxes will be compared. The projection assumes the continuation of forest management practices documented in the period 2000-2009 (Korosuo et al., 2021). This way, the FRL provides a means to account for the impact of policy changes on the net GHG fluxes from forests, while factoring out the impact of age-related forest dynamics (Grassi et al., 2018). The assessment of the FRLs for the period 2021-2025, finalised after a two-year assessment (Korosuo et al., 2021), shows a 17% reduction in the net forest sink at EU level relative to 2000-2009, associated with an increase in the harvest (+16%) driven by the fact that large areas of forest are progressively reaching harvest maturity. A declining sink for the whole LULUCF sector at EU level by 2030 is also reported by National Energy and Climate plans (EC, 2020c).

Identifying the most effective mitigation strategies in the forest sector requires a system perspective (IPCC, 2007; Kurz et al., 2016; IPCC, 2019b), which implies analysing the effect of forest conversions to/from other land uses, the fluxes between forest carbon pools (including living biomass, dead organic matter and soils) and of the pool of harvested wood products, and the interactions between the forest sector and other sectors (Figure 2).

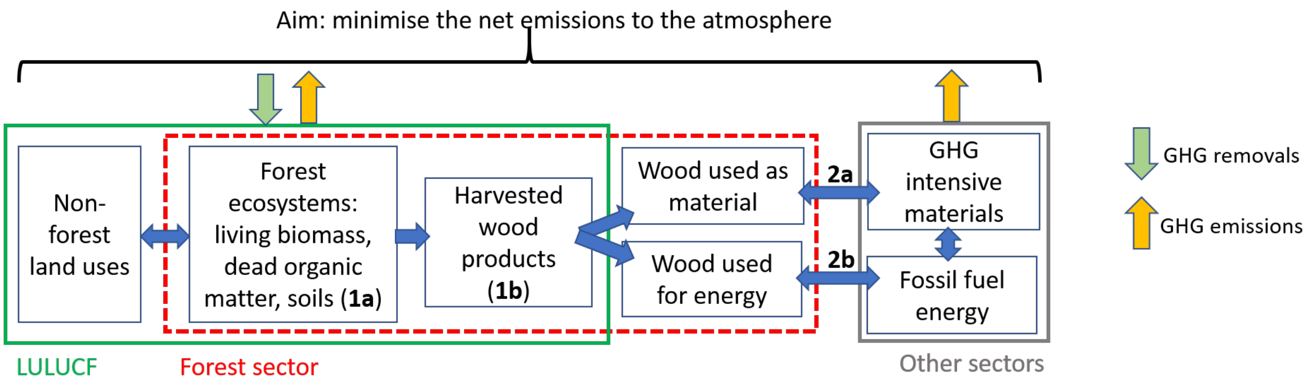

Figure 2. A system perspective of the role of the forest-based bioeconomy in climate change mitigation includes sectors beyond the LULUCF sector, and covers different mitigation options: increasing carbon stocks (1a and 1b) and substitution effects (2a and 2b). Source: IPCC, 2007.

Conceptually, the forest-based bioeconomy can contribute to climate change mitigation by:

1) Increasing carbon stocks (creating a 'net sink'):
   a. In the forest land pools: living biomass, dead organic matter (dead wood and litter) and soils,
   b. In the HWP pool;
2) Substitution effects, i.e. using wood to replace:
   a. GHG-intensive materials (e.g. cement, steel, etc.),
   b. Fossil fuels for energy.

Trade-offs and synergies exist among these options, but are often not fully considered in the literature (e.g. see the review by Böttcher et al., 2021). The first trade-off occurs between increasing the carbon stocks of forest pools (1a) and making more wood available for the other options: as also shown in the context of FRLs (Box 1), in the short term more harvest means less net forest sink. Within the other options, a synergy can occur between 1b and 2a, i.e. HWPs can store carbon over the long term and at the same time they can substitute GHG-intensive materials, while trade-offs occur between 1b and 2b and between 2a and 2b, i.e. wood cannot be used at the same time for both material and energy substitution, even though most wood is eventually used for energy at its end of life. Another trade-off can occur between domestic and imported wood harvest, i.e. reducing the harvest in the EU might increase the harvest from forests outside the EU, effectively displacing GHG emissions. This trade-off is not analysed further in this brief.

The effect of these options on GHG emissions is reflected in the national GHG inventories, which follow standardised formats recommended by the IPCC and agreed by the Parties to the UNFCCC. Changes in carbon stocks are explicitly accounted for in the LULUCF sector, whereas the substitution effects are implicitly reflected in GHG emissions of other sectors. In line with internationally agreed rules (IPCC, 2006, 2019a), the harvesting of biomass leads to direct emissions of carbon to the atmosphere (i.e. instantaneous oxidation), unless it can be shown that the biomass enters another carbon pool, such as dead wood, litter or soil, or is used to produce HWPs. In this way, biomass harvested for its use as energy is fully accounted for and reported as instantaneous GHG emissions under LULUCF. To avoid double counting, these emissions are zero-rated in the energy sector. The following sections focus on the net carbon sinks and on the material substitution effects[4].

2. What are the prospects for EU forests as carbon sinks?

According to the IPCC Guidelines for national GHG inventories (2006, 2019a), the change in forest carbon stocks can be estimated using two different methods: the *Gain-Loss Method*, which includes all processes (i.e. forest growth, mortality, anthropogenic and natural disturbances) and the *Stock-Difference Method*, which can be used where carbon stocks in relevant pools are measured at two points in time (e.g. in national forest inventories). Countries may select either of those methods, based on the availability of reliable data (EEA, 2020).

A good approximation of the net growth of biomass carbon stocks[5] ('net C sink') in EU forests can be provided by the difference between the net annual increment (i.e. wood produced in forests annually, also referred to as gross increment, minus the natural mortality including natural disturbances) and fellings (Figure 3).

[4] The use of wood for energy, including the link between LULUCF and REDII, is extensively covered in Camia et al. (2021).
[5] The forest biomass pool (living biomass) represents about 90% of the net forest sink in the EU (average 2016-2018, EEA, 2020). The CO_2 fluxes in other pools may be important in specific cases (e.g. organic soils, or dead wood after a natural disturbance event). The soil pool is a significant contributor to the carbon sink given the large amount of carbon it stores.

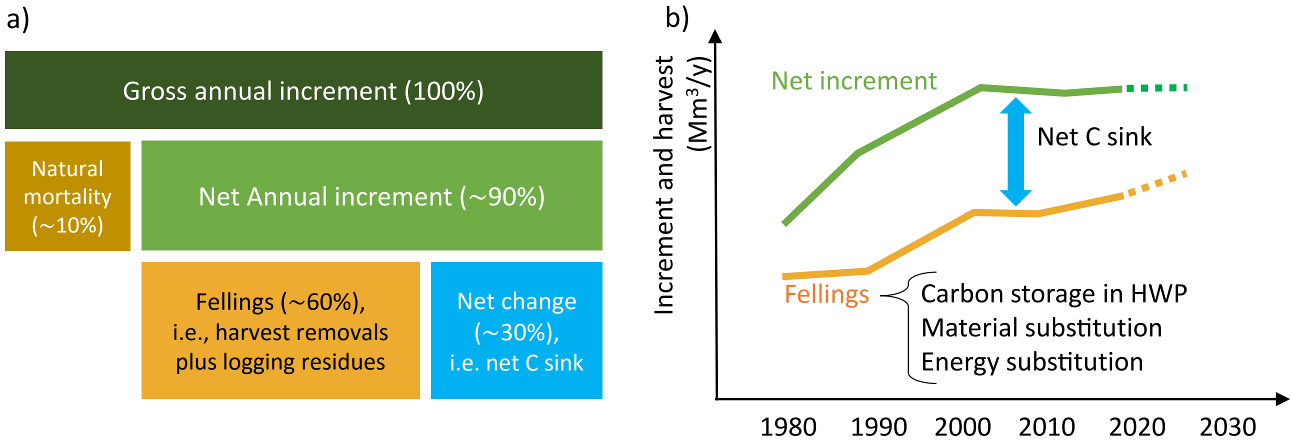

Figure 3. a) Main components determining the net carbon sink (blue box) in forest biomass; the numbers are approximations for the EU (2004-2013), based on Camia et al. (2021). b) Conceptual illustration of the historical trend in the net increment and fellings (based on Nabuurs et al., 2013) of forest biomass and their short-term projected evolution (based on FRLs, Korosuo et al., 2021).

The net forest carbon sink can increase if the total gross annual increment increases, the natural mortality decreases, or the harvest levels and the associated logging residues are reduced, or a combination thereof. However, trade-offs also exist between these components. First, increasing the forest carbon sink may lead to the storage of large amounts of carbon per unit area. This is positive for the climate, because the more carbon is stocked in the forest, the less is in the atmosphere. However, carbon-dense forests may release a relatively greater amount of carbon than low-carbon forests if subjected to natural disturbances such as insect outbreaks (Forzieri et al., 2021) or wild fires (Lippke et al., 2011). Also, while reducing the harvest would increase the net forest sink in the short to medium term (2030-2050, e.g. Valade et al., 2017), it would slow down forest growth in the long term, with a likely consequent decrease (saturation) in the net forest carbon sink at stand level (Smyth et al., 2020)[6]. Overall, it is widely acknowledged that a sustainable harvest can address the issue of sink saturation (by sustaining forest growth), transfer carbon to HWPs (IPCC, 2019a) while also providing socio-economic benefits.

The gross increment of forest biomass is influenced by many factors. At global level, indirect human-induced environmental change (e.g. CO_2 fertilisation[7], climate change, nitrogen deposition) is considered to be the main driver behind the current faster tree growth compared to the past, and the main reason for the current net global land sink (Friedlingstein et al., 2020). At the local level, forest growth is significantly affected by age-related dynamics (younger forest stands typically grow faster than older forests), tree breeding, the local climate and soil conditions, and forest management. The latter may include practices to enhance forest productivity (e.g. Nabuurs et al., 2017), forest restoration techniques to increase forest carbon stocks (Böttcher et al., 2021) and the conversion from coppice[8] to high forests. However, it requires regional-level assessments of the feasibility and impacts of specific forest management practices.

The gross increment of forest biomass can also increase with new forest area. In the EU, the new forest area since 2000 (about 7 M ha, out of a total forest area of 167 M ha in 2018) contributes a net sink of about

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[6] The impact of aging on the net forest sink is complex because it is affected by many factors (climate, CO_2 fertilisation, soil, etc.) and remains controversial: while some studies suggest that old-growth forests may remain a sustained net carbon sink (e.g. Luyssaert et al., 2008; Curtis and Gough, 2018) others suggest the opposite (Zhu et al., 2018; Pugh et al., 2019). Even if old-growth forests remain a sink, however, this sink tends to be smaller than in younger forests (Gundersen et al., 2021; Luyssaert et al., 2021). This observation does not undermine the essential role of old-growth forest as carbon reservoirs.

[7] The increasing CO_2 concentration in the atmosphere stimulates photosynthesis.

[8] The coppice system is traditionally applied to broadleaf forests devoted to fuelwood production, mostly regenerated from shoots, with rotation periods of < 20 – 40 years.

-45 Mt CO_2/yr (EEA, 2020). The plan to plant at least three billion trees in the EU by 2030 (EC, 2020d) would yield an additional sink of the order of -15 Mt CO_{2e}/yr[9] in the medium term.

Despite the new forest area (typically characterised by faster growth rates), the net annual increment at EU level appears rather stable since 2000 (Nabuurs et al., 2013). Recent evidence (SoEF, 2020) suggests a positive trend in the net annual increment in some areas (Northern and Central-Eastern Europe), but there is not enough information to draw conclusions at EU level. Country projections in the context of FRLs (Box 1, Korosuo et al., 2021) seem to point to a further modest increase in net increments up to 2025, but the associated positive impact on the net forest sink is reversed by the increase in harvest due to large areas of forest progressively reaching harvest maturity (Grassi et al., 2018, see Box 1). Some studies also suggest that the positive CO_2-fertilisation effect is approaching saturation (e.g. Wang et al., 2020).

Natural mortality is only to a limited extent under human control, and current evidence suggests an increase in natural disturbances in the EU forests in the past two decades (Seidl et al., 2017; Camia et al., 2021). Tree species diversification as well as an improvement of stand complexity may strengthen forest resistance to increasing disturbances (Jactel et al., 2017). Adaptive management strategies may improve the resilience and functionality of forests at stand and landscape level, and thus help withstand natural disturbances (Lindner et al., 2014). Strategies such as setting aside forest areas (e.g. establishing protected and restricted areas) would help preserve the multi-functionality of forests while ensuring synergies between adaptation, mitigation and biodiversity conservation (Smith et al., 2020; Böttcher et al., 2021). The impact of natural disturbances on the carbon balance at national scale largely depends on the management following the event (e.g. salvage logging), and the carbon fluxes among the pools, and between the pools and the atmosphere. If lateral carbon fluxes (i.e. HWP inflows) are considered, the potential for mitigation may be improved (Pilli et al., 2021). Overall, however, the potential to reduce the impact of natural disturbances in the medium term is very uncertain.

With regard to fellings, country statistics suggest a modest increase in the EU in the past decade (about 6% between 2010 and 2018, FAOSTAT, 2021). However, national statistics for some MS are highly uncertain (e.g. Pettenella et al., 2021; Kallio et al., 2018). At EU level, this uncertainty is also demonstrated by the fact that country statistics on wood use until 2015 are up to 20% higher, and show a slightly greater increase over time, than those on fellings (see Fig. 19 in Camia et al., 2021). Evidence from remote sensing points to a recent significant increase in final fellings (Ceccherini et al., 2020, 2021), which can only be partly explained by natural disturbances. However, since small-scale forestry activities (thinning and selective logging) could not be detected by that study, but are significant in many MS, this evidence cannot be used to draw direct conclusions about the total harvest.

Overall, while a significant increase in the forest sink would be required to meet the EU climate objectives in the medium term (2050), both the current and the projected trends of its determinants as shown in Figure 3 (gross increment, natural mortality, fellings), as well as the country projections up to 2025 (Box 1), rather suggest a declining net forest sink in the short term. Reversing this trend would require an extraordinary and urgent increase in the net annual forest increment, mainly through forest management practices and new forest area. Part of this extra increment could also increase the potential for carbon storage in HWPs and for material substitution, as illustrated in the following sections.

[9] This approximation assumes that 3 billion trees correspond to about 2-3 M ha of forest, and considers the average net sink of young forest area (about 6 t CO_2/ha/yr in 'land converted to forest land', i.e. < 20 years old) from the EU GHG inventory (EEA, 2020).

3. What is the contribution from carbon stored in harvested wood products?

The carbon stock change in the HWP pool[10] reported in the national GHG inventories follows the IPCC Guidelines (2006, 2019a) and is based on the balance of the annual inflow of harvested and processed domestic wood[11] and the outflow from the pool through oxidation of the carbon in wood products that reach their end-of-life (Figure 4). The latter is based on default half-life values attributed to each wood commodity[12].

When the inflow is greater than the outflow, the amount of carbon stored increases and the HWP pool acts as a 'net carbon sink' (see footnote 1). By contrast, when the inflow is less than the outflow, the amount of carbon stored in the HWP pool decreases and the pool acts as a 'net carbon source'. In the period 1990-2015, the carbon stored in HWPs increased from 2.5 to 2.8 tonnes of carbon per capita in the EU (SoEF, 2020).

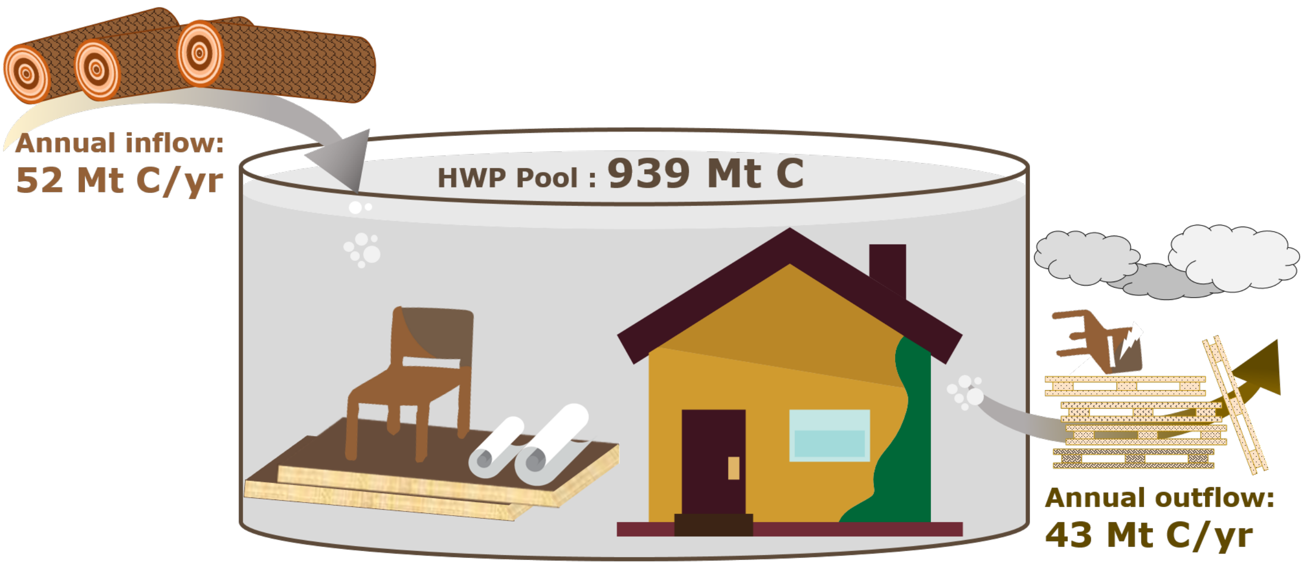

Figure 4. The carbon dynamics of the HWP pool in 2018 for the EU[3] (EEA, 2020).

Thus, one way to increase the carbon storage in HWPs is to increase the inflow by further increasing the harvest (Pilli et al., 2015). However, this generally reduces the carbon sink in the forest pool in the short to medium term. For example, according to Pilli et al. (2017), increasing the harvest by 20% by 2030 would increase the net carbon sink in HWPs by 8%, but the forest carbon sink would decrease by 37% compared to the average of the period 2000 – 2012.

The net carbon storage in HWPs is influenced by the quantities of domestically harvested industrial roundwood, industrial wood residues and secondary wood, i.e. the main resource materials for HWPs[13]. This correlation is illustrated by comparing the trends of industrial roundwood removals (green columns in Figure 5a) with the HWP net carbon sink (orange columns in Figure 5b). The net carbon sink in HWPs in Fig. 5b increased continuously until 2007 because the inflow was increasing. However, due to the economic crisis in 2008 and

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[10] In the EU, the total C stock in forests is estimated at approximately 20,000 MtC (SoEF, 2020), with 9,500 MtC in aboveground living biomass. This value is about ten times higher than the C stock in HWPs in use (see Figure 4).

[11] The imported HWPs are excluded from the national GHG reporting of the importing country under the Production Approach. Thus, the inflow to the national HWP pool is determined only from the relative roundwood produced (IPCC 2006, 2019a). With regard to the exported HWPs, Johnston and Radeloff (2019) and Sato and Nojiri (2019) noted that the traded feedstock (i.e. the amount of raw wood directly exported to other countries) could not be accounted for within the HWP mitigation potential of both of the exporting and the importing countries. However, under an IPCC Tier 3 approach, the export may be considered in the GHG inventories if the fate of the exported HWPs (as roundwood or semi-finished products) can be determined, i.e. if data are available on the allocation of HWPs to specific commodities in the importing country.

[12] A half-life is the number of years it takes to lose one-half of the material currently in the pool (IPCC, 2006). The IPCC Tier 2 approach, largely used by most EU countries, attributes a default half-life value of 35, 25 and 2 years to sawn wood, wood panels and paper with paperboard, respectively. Under a Tier 3 approach, countries might choose to apply country-specific half-life values and categories of semi-finished HWPs if reliable and transparent data is available.

[13] Based on Camia et al. (2021), out of the total annual wood removals used in the EU for the year 2015 (523 Mm^3 + 39 Mm^3 of unreported removals + 18 of net imports = 580 Mm^3 solid wood equivalents) about 32% (185 Mm^3) ended up as solid products (sawn wood and wood-based panels). The values from Camia et al. (2021) are slightly higher than the country statistics shown in Fig. 4 because they are derived from reported uses, refer to a different year (2015) and include data for the UK.

the consequent decline in industrial roundwood, the net sink in HWPs dropped from -67 Mt CO_{2e}/yr in 2007 to -29 Mt CO_{2e}/yr in 2009. On the other hand, the total harvest removals (i.e. industrial roundwood and fuelwood, the sum of the green and brown columns in Fig. 5a) tend to correlate negatively with the net carbon sink in forest land (blue column in Fig. 5b).

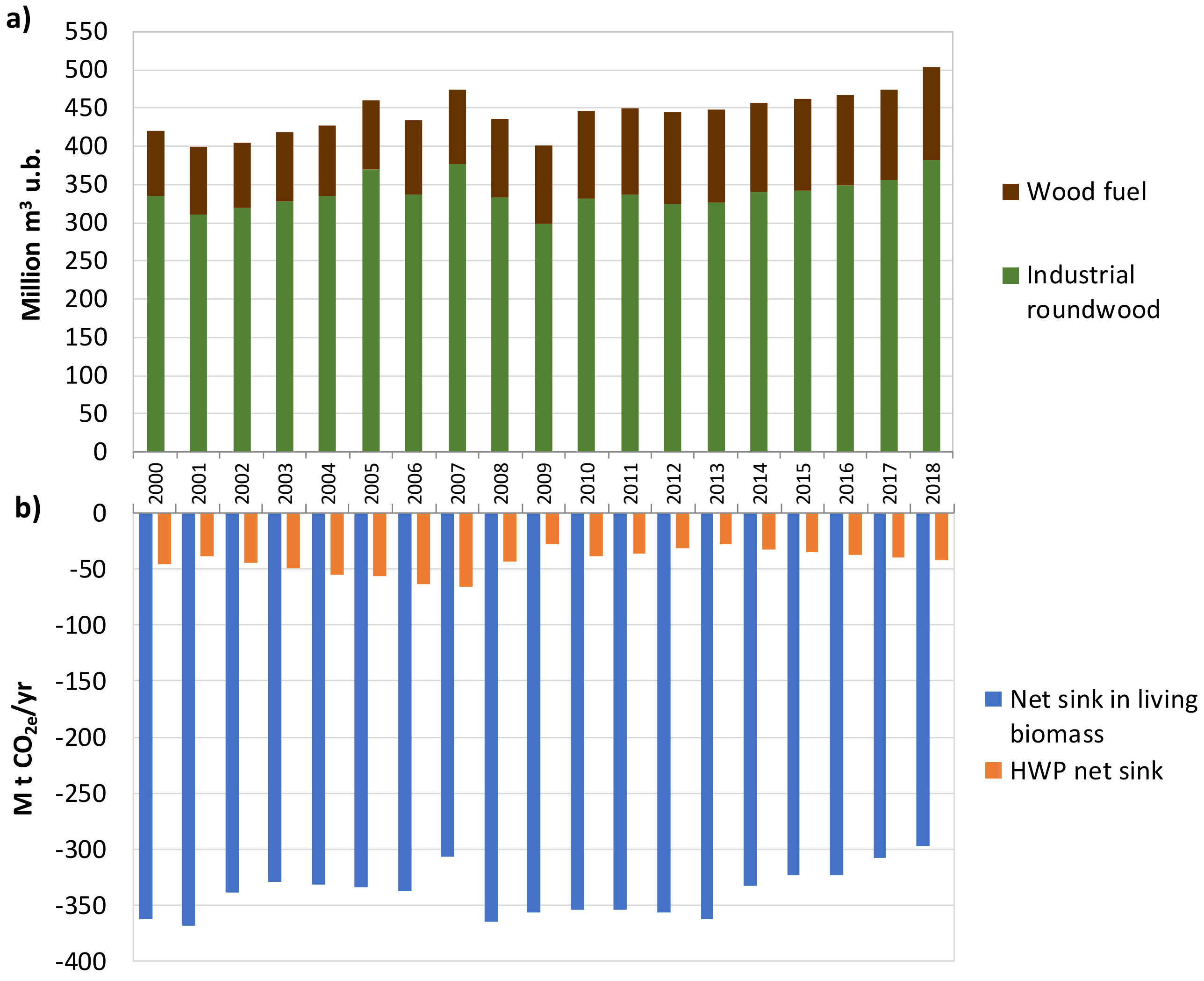

Figure 5. Evolution of a) roundwood removals by wood product (industrial roundwood and wood fuel, FAOSTAT, 2021); b) net carbon sink in living biomass in 'forest remaining forest' not accounting CO_2 emissions from fires [14] and net sink in HWPs from the EU GHG inventory (EEA, 2020) in the EU from 2000 to 2018.

Another way to increase the net carbon stored in HWPs is to change how the harvested wood, industrial wood residues and secondary wood are used for different commodities. A shift to wood products with a higher service life, e.g. from paper to construction timber, would slow down the outflow and help conserve or enhance the growth of the HWP pool while maintaining a stable harvest over time. Research and innovation in this area can play a key role in that shift[15].

[14] Average emissions from fires in the EU, not included in Figure 5, amount to 3.7 Mt $CO_{2e/yr}$ for 2000-2018 (EEA, 2020).
[15] A mapping exercise conducted as a contribution to this brief by the European Climate, Infrastructure and Environment Executive Agency (CINEA) and the Bio-based Industries Joint Undertaking (BBI-JU) identified 8 LIFE and 8 BBI-JU R&I projects addressing the shift towards long-lived wood-based products, e.g. LIFE EcoTimberCell, LIFEWOOD and H2020 Build-in-Wood. Research and innovation on this specific topic was supported also by FP6, FP7, H2020 and other EU framework programmes.

4. What climate change mitigation benefits can be achieved by using wood to replace GHG-intensive materials?

Estimating the effects of using wood instead of GHG-intensive materials (e.g. cement, steel, etc.) is important to communicate the benefits of the forest sector beyond the carbon sink (thus the importance of a "system approach", see section 1) and to inform the development and monitoring of climate-related and other policies. However, estimating the material substitution effects is more complex than estimating a net carbon sink.

The estimation of the net carbon sink in forest pools and in HWPs follows standard IPCC methods, which assess GHG emissions and removals when and where they occur across national economy sectors. The net carbon sink for the historical period is explicitly reflected in the GHG inventories; the projected net carbon sink can be assessed either in absolute terms or as deviation from a "reference" scenario, e.g. current situation or business-as-usual (BAU) scenario.

By contrast, the IPCC does not provide methods to assess substitution benefits, because they are implicitly included in non-LULUCF sectors (e.g. as reduced emissions from cement or steel production). In order to assess the specific impact of using wood to substitute GHG-intensive materials, the scientific literature (e.g. Rüter et al., 2016) typically: (i) uses the life cycle assessment (LCA) methodology, i.e. a structured, comprehensive and internationally standardised method used to assess potential environmental impacts associated with a product's life cycle (Giuntoli et al., 2019) and (ii) assesses the substitution benefits only as a deviation from a "reference" scenario. As a result, the products that are already made of wood and replaced by wooden products are typically not considered as having a substitution benefit, because they are not additional. In other words, the "additionality" is implicit in the concept of "substitution".

In practice, the material substitution benefits, i.e. the GHG emissions avoided by using wood products instead of other fossil-based materials, are assessed by multiplying the amount of wood used to substitute other materials (on top of the reference case) by a substitution factor (SF). This parameter strongly affects the final results and is characterised by a high level of uncertainty. It depends on many factors such as the type of non-wood product being substituted, the energy-mix used in the production of the substituted product, the wood-based material used for the substitution, the quantity of wood products providing real substitution effects (which is relatively low compared to the total quantity of wood removed from forests), the lifetime of the product and the end-of-life management (Leskinen et al., 2018). Furthermore, many other assumptions (feasibility of replacing concrete or steel products with wood products and producing the same mix of wood products with an increased harvest) are needed to assess the mitigation potential of material substitution (Howard et al., 2021).

Values for SFs in the literature range from 1.1 to 2.1 t C / t C (Table 1), which means that for each ton of carbon in wood products that substitute non-wood products, there is an average reduction in emissions to the atmosphere of between 1.1 and 2.1 tons of carbon. Many studies (e.g. Rüter et al., 2016) refer to the average SF proposed by Sathre and O'Connor (2010), equal to 2.1 t C /t C; however, more recent studies revised the SF downwards. Seppälä et al. (2019), estimate an average SF for Finland of 1.1 t C /t C, and a recent literature review by Leskinen et al. (2018) proposes an average SF equal to 1.2 t C /t C.

Table 1. Average values for the substitution factor (SF) from the literature. SFs may vary according to, for example, the more specific product category, the specific type of wood-based material and the end use of the wood product.

Source	Year	SF average (t C / t C)	SF detailed for product categories (t C / t C)
Rüter et al. from Sathre and O'Connor, 2010)	2016	2.1	-
Seppälä et al.	2019	1.1	-
Leskinen et al.	2019	1.2	1.3 structural construction 1.6 non-structural construction 2.8 textiles 1-1.5 others (chemicals, furniture, packaging)
Knauf et al.	2015	1.5	1.30-2.40 structural construction 1.10-1.62 non-structural construction 1.66-1.62 furniture 1.35-1.62 others

Several studies assess the climate benefits of the substitution effect of wood-based materials in the EU, with values ranging from -18 Mt CO_{2e}/yr to -43 Mt CO_{2e}/yr (Table 2).

Table 2. Climate change mitigation benefit of using wood to replace other materials in the EU, based on specific studies.

Source	Year	Value (Mt CO_{2e}/yr)	Time horizon	Key assumptions
Nabuurs et al.	2017	-43	2050	One quarter of sawn wood ends up in structural longer-term use, displacing other materials
Rüter et al.	2016	-34	2021-2030	Business-as-usual scenario achieving EU energy and climate targets for 2020
		-18		A general shift from energy to material use, plus cascade uses lead to additional -18 Mt CO_{2e}/yr
Jonsson et al.[16]	2021	-28	2030	Additional mitigation potential when assuming increased wood-based construction
		-2		Additional mitigation potential assuming the demand for biochemicals and biofuels increases
		-35		Additional mitigation potential when combining previous assumptions

By contrast, Holmgren (2020) estimates an absolute annual benefit of -249 Mt CO_{2e}/yr (with a total climate change mitigation of the forest sector equal to -806 Mt CO_{2e}/yr, i.e. 20% of all EU fossil emissions). This estimate is about ten times higher than the values typically provided by the other assessments, as this study attributes a substitution benefit to the entire current solid wood production, ignoring the fact that many products are already produced from wood. This is different from all the other studies on material substitution, where the benefits are considered only when one material replaces another, not for all uses of that material.

[16] The assessment by Jonsson et al. (2021) models the future evolution of the wood-based product market (e.g. the foreseen increase in the wood construction quota, as in Hildebrandt et al., 2017), the expected shares of different wood-based products (shares of different end-uses, as in Merivuori, 2009) and distinguishes different expected lifetimes of each category (applying SF assessed in Valade et al., 2017).

Furthermore, trade-offs need to be assessed: if the greater use of wood material is associated with an increase in harvesting, this will likely negatively impact the forest carbon sink in the short to medium term (2030-2050). In this regard, most studies explore various combinations of increased harvest levels and realistic shifts in HWP commodities. These studies conclude that, within a short to medium time horizon, the additional mitigation potential provided by the material substitution effect is unlikely to compensate for the reduction of the carbon sink in forest ecosystems affected by the increasing harvest (Jonsson et al., 2021; Rüter et al., 2016; Valade et al., 2017; Seppälä et al., 2019; Kalliokoski et al., 2020; Soimakallio et al., 2021). If the current shares of HWP commodities are maintained, this conclusion holds even assuming the highest SFs (e.g. 2.1 t C/t C, as indicated by Seppälä et al., 2019 and Kalliokoski et al., 2020). Another recent study concluded that, although lower than expected in the long term, climate change mitigation effects of wood product use can play a role (Brunet-Navarro et al., 2021). Only with longer time horizons (i.e. from 30 years to more than 100 years) can active forestry with high harvest levels and an efficient utilisation of biomass residues for the replacement of GHG-intensive products yield an annual substitution effect larger than the net decrease in the carbon sink linked to the increase in the harvest (Taverna et al., 2007; Gustavsson et al., 2021). At the same time, the average substitution benefits of wood-based products can be assumed to decline in the future, as the emissions from the energy sector are expected to decline (e.g. Peñaloza et al., 2018). This is why policies to promote substitution benefits are more relevant in the short term when the share of renewable energy sources is relatively low (Brunet-Navarro et al., 2021).

5. How can the forest-based bioeconomy effectively contribute to climate change mitigation?

Overall, by assessing the trade-offs among different options (i.e. net carbon sink in forest land vs. other mitigation options) it becomes evident that it is necessary to significantly increase the net annual forest increment in order to reverse the current trend of declining sinks and maintain or slightly increase the current harvest levels and thus align the contribution of the forest-based bioeconomy with the EU goal of climate neutrality by 2050. While this general finding may be useful to inform policy options with a different temporal focus (short vs. long-term), it needs to be complemented by more specific recommendations based on specific integrated modelling and tailored to region-specific circumstances[17].

Furthermore, a holistic assessment is necessary to guide policies towards an effective and resilient contribution of the forest sector to climate change mitigation (see the "climate smart forestry" approach, Verkerk at al., 2020). This entails, among others, assessing the impact of age-related dynamics (i.e. more areas of forest reaching harvesting maturity) and the risk of non-permanence of the carbon stored in the forest pools (due to a possible increasing impact of fires, pests, windstorms, droughts, etc.). For example, where a future increase in harvest is expected because of forest aging in managed forests or adaptation needs (e.g. to decrease the susceptibility or increase the resilience of forests to climate change effects), then using this 'unavoidable' extra harvest in wood products characterised by higher service lives and higher substitution benefits would bring climate benefits compared with a business-as-usual scenario of wood use.

[17] See the study by Smyth et al. (2020) for Canada, as an example of the kind of analysis that would be needed.

Knowledge gaps

1. Uncertainties about the actual net forest increment and harvest rate from country statistics may be high, at least in some cases. Remote sensing techniques can complement official statistics in detecting harvested forest area, at least for final fellings.
2. The development of more country-specific estimates of decay functions of the different wood product commodities would help reduce the uncertainty in the current and future potential of the net HWP sink. Greater national and regional specificity is needed in order to ensure particularity of use and discharge of wood products, i.e. better tracking of half-lives of commodities instead of the three types of semi-finite products.
3. More comprehensive assessments of the Substitution Factors (i.e. the GHG emissions avoided by using wood products instead of other fossil- or mineral-based materials) in different scenarios will contribute to more accurate assessments of the climate benefits of wood substitution. In particular, there is still insufficient knowledge on the climate impacts of emerging forest products (textiles, packaging, chemicals, etc., see Leskinen et al., 2018).
4. The continuation of efforts to understand and model the evolving competing demands for wood at national, EU and international level, including risks of emissions displacement outside the EU, is key.
5. Better knowledge is needed about the future impacts of climate change, natural disturbances (e.g. fires, pest, windstorm, droughts) and adaptive forest management interventions on forest growth and carbon stocks and about the impact of various forest management practices on these elements.
6. Integrated modelling frameworks at regional level would support recommendations that take into account local circumstances.

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