

RESEARCH ARTICLE

Options to improve the carbon balance of the harvested wood products sector in four EU countries

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Abstract

Harvested wood products (HWP) may contribute to climate change mitigation by storing carbon and by replacing energy-intensive materials and fossil energy, reducing greenhouse gas (GHG) emissions. However, when assessing improved HWP utilisations, interactions between wood use pathways, the carbon stock dynamics, and the resulting effect on the GHG balance are still not well-understood. This research aims to assess the carbon sequestration effects of alternative wood product utilisations in four European Union (EU) countries. We conducted a material flow analysis of wood uses in France, Finland, Germany, and Spain for 2017 taking into account national production, imports, and exports. Then, we quantified the future dynamics of carbon stock in the HWP through time, assuming the same as in 2017 input and ignoring the forest sink. We then ran six alternative scenarios: two energy-focused (Energy, Energy+), two material-focused (Cascading, Material), one with extended half-life of the wood products (HL) and one as business as usual. For the simulation period (2020–2050), the material scenario leads to the highest mitigation benefits with a cumulative HWP net CO₂ removals of −502 Mt CO₂ for Germany, −290 Mt CO₂ for France, −118 Mt CO₂ for Spain, and −116 Mt CO₂ for Finland over the 30 years. The Energy+ scenario with an increase in wood usage for bioenergy generates a loss of the HWP pool of 351, 80, 77, and 6 Mt CO₂ for the same countries, not accounting for energy substitution effects. Overall, our results suggest that the HWP carbon stock can be increased in the short-medium term by prioritizing the use of wood for material purposes, while maintaining constant harvest. The HWP mitigation potential differed greatly according to national wood industry characteristics. Hence, tailoring the HWP mitigation strategies to the specific characteristics of the national wood chain would enhance the HWP climate benefits.

KEYWORDS

carbon stock, cascading use, circular bioeconomy, forest bioenergy, GHG emissions reduction, harvested wood products

1 | INTRODUCTION

Forests play a crucial role in mitigating climate change due to their ability to absorb carbon dioxide (CO₂) from the atmosphere and store it durably in the form of carbon (C) in the biomass. In addition, when trees are harvested, part of the C in the stems is transferred to the harvested wood products (HWP). The overall forest mitigation potential includes the sum of three effects: increasing carbon stocks in the forest, increasing carbon stocks in the HWP and using HWP to substitute other materials or fossil energy use (Johnston & Radeloff, 2019; Myllyviita et al., 2021).

While harvesting decreases the carbon stored in forests in the short term, part of the carbon is transferred to HWP and can remain sequestered for a certain time depending on the application, preventing it from being released into the atmosphere. In the European Union (EU), the increase in HWP C stock over the last two decades was on average 40 Mt CO₂ equivalent year⁻¹, corresponding to about 10% of the entire EU forest CO₂ sink (EEA, 2022). Changes in the C stock of HWP under the current use are reported annually to the United Nation Framework Convention on Climate Change (UNFCCC) under the Land Use, Land-Use Change and Forestry (LULUCF) sector. However, the potential future climate benefits of the wood-based bioeconomy are uncertain (Verkerk et al., 2021). This is because the HWP mitigation varies depending on the amount of wood, its origin and its type of use, which affect the duration of the C storage. For example, it has been calculated that construction of new wooden buildings could store 0.01–0.68 Gt C year⁻¹ globally, compared to the actual C stock in long-lived wood products of 0.05–0.09 Gt C year⁻¹ (Churkina et al., 2020; Nabuurs et al., 2022).

In addition, HWP may substitute more energy-intensive materials, such as steel or concrete, or fossil energy. The benefits of using wood for material and energy substitution depend on the specific use of wood, as expressed by the wide range of displacement factors reported in the literature (e.g. ranging from 1.0 to 3.0 for material substitution, Sathre & O'Connor, 2010a). An average displacement factor of 2, for example, means that each tonne of C in wood that substitutes non-wood products, corresponds to an additional emission reduction of 2 tonnes of C. Given the uncertainty in displacement factors we focus in this study on the mitigation potential of C stored in wood products only as this is the one most tangible effect of the use of wood products.

There are many factors that may affect the estimations of the C stock in HWP at national level, one is the C accounting approach (Brunet-Navarro et al., 2016; Jasinevičius et al., 2015). Carbon accounting is a method to measure, delineate and report in a standardised way the amount of carbon dioxide emissions and removals. The

Intergovernmental Panel on Climate Change (IPCC) describes four C accounting approaches: *stock-change*, *production*, *atmospheric flow*, and *simple decay* (Gitarskiy, 2019). These approaches differ for the boundaries they consider, that is, if and how import and export are included. In the *production* approach, which is the approach commonly used by the countries in the national greenhouse gas (GHG) reporting under the UNFCCC, the exported semi-finished products contribute to the national C stock, if they are fabricated with domestic wood resources. In the *stock change* approach, the exported semi-finished products are not taken into account (Eggers, 2002; Karjalainen et al., 2003; Pingoud et al., 2009).

Two other factors that influence the amount of C in HWP are the lifespan (i.e. allocation of raw material shares to product groups) and shares of re-use of wood products (Brunet-Navarro et al., 2017; Budzinski et al., 2020). To this regard, several studies indicate that the cascading use of woody biomass can improve the climate impact of HWP (Bais-Moleman et al., 2018; Mair & Stern, 2017; Vis et al., 2016). Cascading wood utilisation has been defined as wood being processed into the highest quality product first, and re-used and recycled thereafter to lower quality uses with the aim to prolong the length of total use and thus extend biomass availability within a given system (Vis et al., 2016). Under this principle, wood is used in the following order of priorities: solid wood products, extended lifespan, re-use, recycling and bioenergy.

An improved use of wood and products can thus reduce the GHG emissions compared to the current situation and can increase the total carbon kept in the product pool. The many variations and effectiveness of these is little researched. A thorough assessment and quantification of the intricate relationship between various wood utilisation pathways, approached dynamically through material flow analysis (MFA), and their consequent influence on carbon stock changes remains unexplored.

The accuracy of the estimation of the HWP contribution to the carbon removals/emissions is strongly dependent on data availability and level of detail and precision. Varying by country and commodity there is still quite an uncertainty in the statistics on production and trade of wood products (Buongiorno, 2018; Kallio & Solberg, 2018; Pettenella et al., 2021), in their rate of recycling and in their end-uses (Jonsson et al., 2021). The development of improved tracking and reporting tools could help to understand the potential benefits of cascading and optimal wood utilisations (Vis et al., 2016). To increase the consistency of wood product statistics the MFA represents one of the most reliable tools (Bais-Moleman et al., 2018; Mantau, 2015). The MFA is quantitative approach to analysing the flow of wood products and materials within a given system or industry. It involves tracking the sources

of wood raw materials, the production and distribution of wood products, and the disposal or recycling of wood waste and by-products.

In the literature, there are few studies employing MFA across various scales, ranging from country-level to the EU level, with varying degrees of detail concerning commodities (Avitabile et al., 2023; Layton et al., 2021; Mantau, 2015). On the other hand, some other type of investigations analyse the impacts of diverse portfolios on alterations in national carbon stocks (Jasinevičius et al., 2017; Parobek et al., 2019; Pilli et al., 2017). However, there is a notable absence of studies that integrate dynamic MFA with dynamic modelling, especially those that incorporate the wood-to-energy sector into their analyses.

This study aims to assess the HWP carbon stock changes due to alternative HWP utilisations. To do so, we first performed a detailed MFA to obtain consistent estimations of wood flows across the wood chain of four country-level case studies: Finland, France, Germany and Spain. Then, we projected the carbon stock change of the HWP pool until 2050 under different wood utilisation scenarios, such as increasing the share of recycled wood and the share of wood used for material purposes.

2 | MATERIALS AND METHODS

Four macro-ecozones were chosen to represent the different climate regions in the EU. For each of them, we chose a representative nation as a case study, including Finland (boreal zone), France (temperate-Atlantic zone), Germany (temperate continental zone) and Spain (Mediterranean zone). We applied the same methodology, as described below, for all the case studies.

We analysed and quantified the wood flows at national level. To do so, we used different data sources: FAOSTAT data, JWEE database and industry conversion factors (Table 1).

Most of the values were extracted from FAOSTAT database, in particular for the production, import and

export of industrial roundwood, fuelwood, sawnwood, wood-based panels (WBPs), wood pulp, paper and paper-board. The bark is not taken into account in the primary source of roundwood from FAOSTAT, such as industrial roundwood and fuelwood. We utilised the UNECE's forest product conversion factors to determine the bark volume. Regarding the raw material input for the different industries, we used the sawlog volume from FAOSTAT for the sawmill sector. For the WBP and pulp industry, the input volumes are obtained by multiplying production data (from FAOSTAT) for the different wood-based commodities with corresponding input coefficients (from Infro).

The volume of by-products resulting from the sawmill and WBP industries is obtained by subtracting the volume of semi-finished product from the volume of raw material. The black liquor, which is the waste product from the kraft process when digesting pulpwood into paper pulp, is calculated through the Infro output table. All the values are converted in solid wood equivalent (swe), using the UNECE conversion factors.

For the energy uses, the main source is the Joint Wood Energy Enquiry (UNECE, 2017). From the "Aggregated data" section, we extracted the wood energy flows from the different sources (direct, indirect and recycled) to the different uses (co-generation, power plant and household). We used the report from 2017 since it was the latest version at time of the analysis. The JWEE is voluntarily, and it is carried out for odd years only. For Spain we extracted the information from the national statistic portal, as data in the JWEE were missing.

After that, the wood flows have been displayed using the Sankey diagram, a common tool to visualise the wood material fluxes at the national scale. The arrows indicate the main wood flows across the wood industry with their thickness representing volume in swe (Figure 1).

Next, the diagrams have been quantified into a python script. The parameters (i.e. arrow thickness) are country specific while the flow structure remains the same for all the countries. The model needs only two hard inputs: the volume of industrial round wood (IRW) and the volume

TABLE 1 Data sources used for the wood flow diagrams.

Data source	Organisation	Data	References
FAOSTAT	Food and Agriculture Organization (FAO)	Production, imports and exports of forest products	FAO (2018)
Industry shares	Infro	Input/output coefficients for wood products industry	Mantau (2010)
Forest product conversion factors	United Nations Economic Commission for Europe (UNECE)	Conversion factors and bark factors	UNECE (2020)
Joint Wood Energy Enquiry (JWEE)	UNECE/FAO Forestry and Timber Section	Energy use of wood, conversion factors	UNECE (2017)
National statistic portal	Spanish government	Energy use of wood	Miteco (2021)

Material flow DE 2017

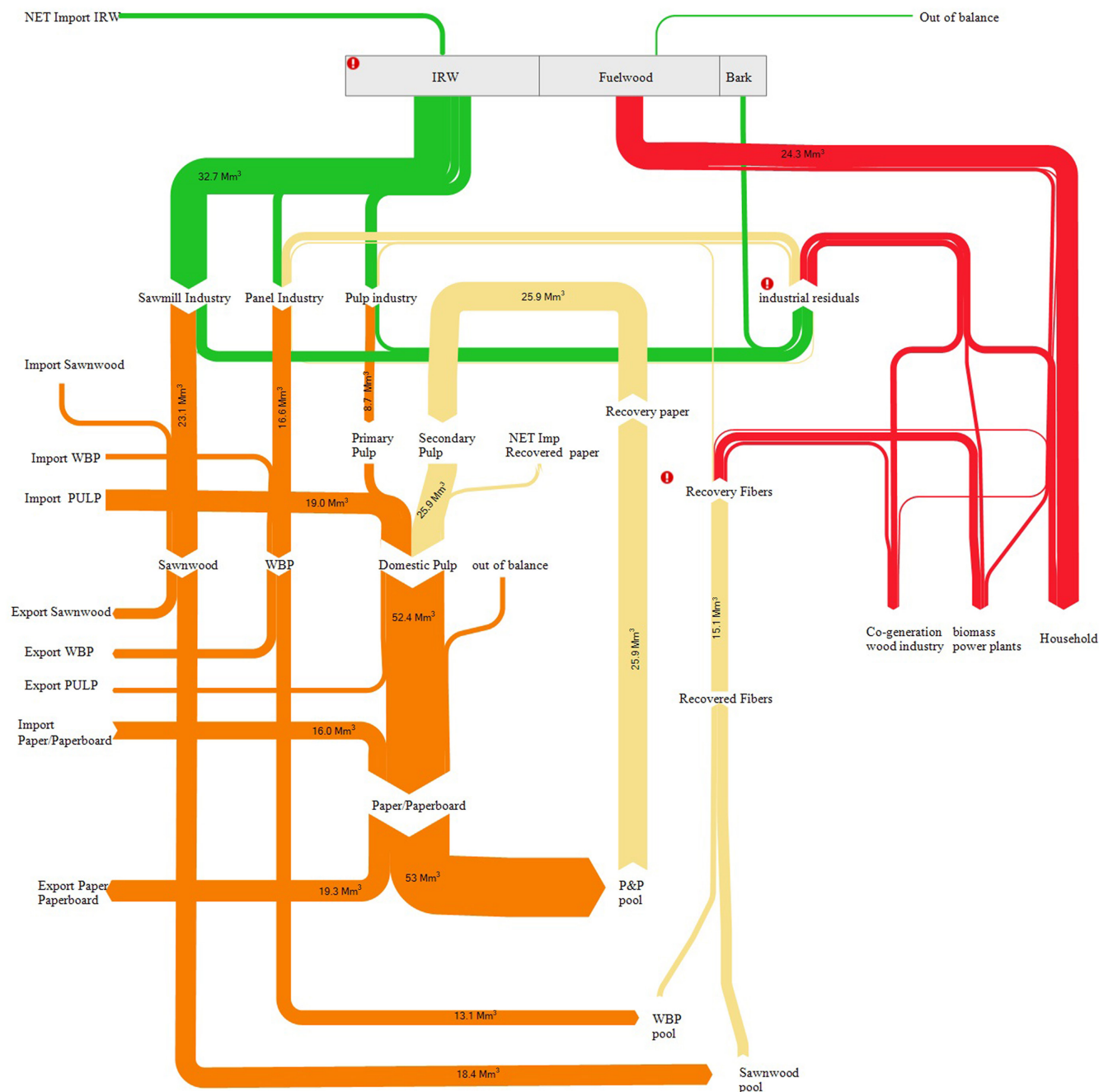
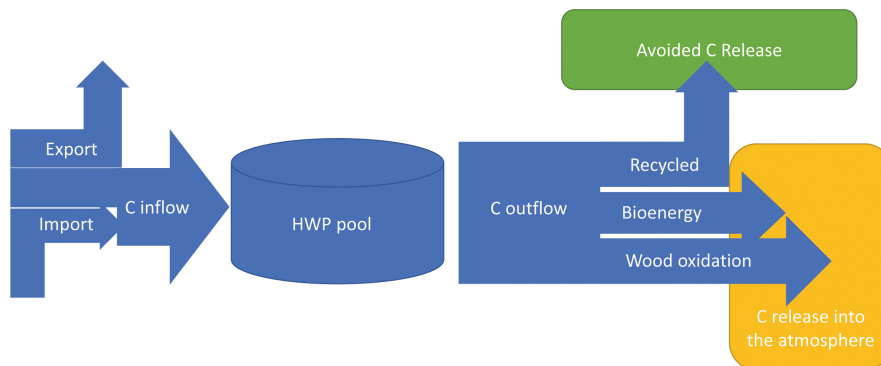


FIGURE 1 Sankey diagram representing the wood industry fluxes for Germany (in 2017), with a relative process unbalance tolerance of 5%. The numbers show the volume of wood in m³. We selected green for the raw wood, orange for semi-finished products, yellow for the recovered fibres and red for bioenergy. IRW, Industrial Roundwood; P&P, Paper and Paperboard; WBP, wood-based panels. Red flag near the process represents input/output unbalance greater than 5%.

of fuelwood produced annually per country. Once these two values are set, the model computes the volume of wood (converted to C) flowing into the main three HWP pools (sawnwood, WBP and paper and paperboard). A simplified example of the HWP carbon fluxes is provided in [Figure 2](#). The yearly carbon inflow is based on apparent consumption, defined as production plus imports minus

exports of the product. At this stage, the carbon stock is calculated by applying the first-order decay equation (the full description in the paragraph below). The outflow is estimated multiplying the amount of C stock by the decay rate derived for each commodity. The C outflow has been then allocated to the end-use according to the country parameters assessed from the MFA. In particular, the share of

FIGURE 2 Scheme of the harvested wood product (HWP) C fluxes for the calculation of the C stock change.



recovered wood is based on the amount of recovered-post consumer wood from FAOSTAT while the share allocated to bioenergy is based on the JWEE. Finally, to calculate the natural oxidation we subtract these two from the total C outflow (Figure 2). In this case, oxidation refers to the portion of HWP removed from the corresponding pools and neither recycled nor used for bioenergy.

2.1 | Carbon stock calculations

The carbon stock has been calculated following the stock-change approach suggested by IPCC. We used the *stock change* approach since it includes the import and excludes the export, resulting in a more realistic representation of the amount of carbon retained inside the country borders.

For each commodity (Paper and paperboard, sawn wood, WBPs) the annual C stock is calculated using a first-order decay equation:

$$C(n+1) = e^{-k} \times C(n) + \left[\frac{(1 - e^{-k})}{k} \right] \times \text{Inflow}(n), \quad (1)$$

where $C(n)$ is the carbon stock at year n . $\text{Inflow}(n)$ in year n is given by multiplying the volume allocated to the wood commodity by the C conversion factor (i.e. the carbon content in kg kg^{-1}). k is the constant decay rate derived for each commodity by Equation (2).

$$k = \frac{\ln(2)}{\text{HL}}, \quad (2)$$

where HL are the half-life values. We used 35, 25 and 2, respectively, for sawn wood, panels and paper (Rüter et al., 2019).

The C stock change is then calculated

$$\Delta C(n) = C(n+1) - C(n). \quad (3)$$

The net C sink of HWP is given by the sum of the annual stock change for each commodity. We then converted the net C sink into CO_2 removal by multiplying it by 44/12. Conventionally the CO_2 removals are reported with negative sign, while emissions with positive one

(Penman et al., 2003). In this paper, we use the same reporting method.

Turning now to the initialisation, we assumed a near steady state at the start of the time series. This is done by averaging the C stock value of the first 5 years of each commodity for which the statistical information was available, in our case 1961–1966 (Rüter et al., 2019). However, in Figure 3, we showed only the value from 1990, to make the graph more readable.

To test the model, we first ran it with the historical input values from FAOSTAT for the period 1990–2020, where we applied constant allocation values based on the wood flow distribution from 2017 (Figure 3). We then compared the output with the official country statistics reported in GHG inventories. Finally, we tested six scenarios to see which strategy yield the highest mitigation benefits.

2.2 | Scenarios

We developed six different scenarios, which differ mainly in how wood is allocated to different wood industries from 2020 to 2050 (see Table 2). In each scenario, we assumed a constant harvest, meaning that the input remains stable throughout the simulation period. The baseline scenario (BAU) kept the allocation and input values constant. In the half-life scenario, we increased the half-life values by 10%. This means that sawn wood produced from 2020 onwards had a half-life value of 38.5 years, the WBP of 27.5 years and paper of 2.2 years, instead of the original values of 35, 25 and 2.

In the Cascade scenario, we gradually increased the portion of recovered paper and recovered wood by 4% points per year for 5 years, reaching +20% points in 2025. After 2025, we kept both at +20% points relative to the baseline.

The Material scenario is based on the Cascade scenario, but in addition we redirected part of the wood assigned to fuelwood to the sawmill industry instead. This scenario involves reducing the flow of fuelwood to bioenergy by 5% points per year from 2020 to 2030. From 2030 to 2050, we reduced the annual amount of fuelwood by half compared to the initial values. This amount of wood

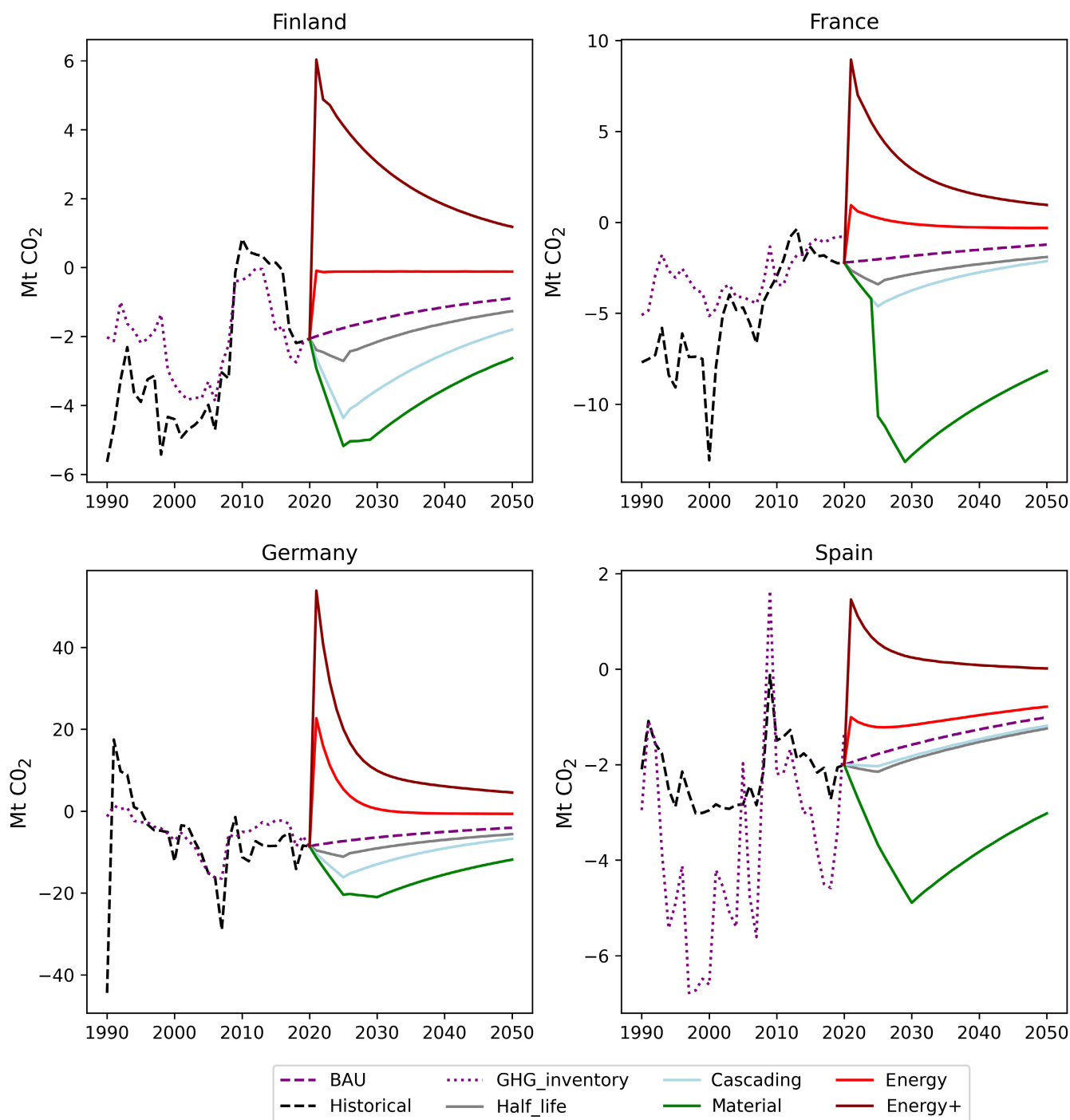
Net CO₂ emissions and removals in HWP

FIGURE 3 Net CO₂ emissions and removals in HWPs. Projected emissions (positive values) and removals (negative values) of CO₂. BAU = constant harvest; Cascade = cascade wood utilisation; Energy = all by-products and post-consumer wood to bioenergy; Energy+ = same of Energy scenario and 50% of material wood to bioenergy; GHG inventory = official country statistic; Half-life = increased half-lives; Material = cascade scenario and 50% of fuelwood to material. The zero line represents a steady state where emissions are equal to removals.

was redirected to the sawmill industry, which gained the additional amount of wood during the same period.

Finally, we developed two bioenergy-oriented scenarios. In the Energy scenario, we redirected the entire amount of by-products and post-consumer wood to bioenergy

generation. The Energy+ scenario is the same as the Energy scenario, but we also redirected 50% of industrial roundwood to the bioenergy sector. The pulp and panel stream were initially utilised to get the raw wood required for increasing bioenergy production. We also sourced it

from the sawmill industry stream if the supply of raw wood was insufficient to cover the increased share of bioenergy.

Among our six scenarios (BAU, half-life, Cascade, Energy, Energy+, and Material), four can be considered plausible, while the remaining two (Energy+ and Material) are more radical. Simulation studies of HWP frequently choose to extend the half-life of wood products and explore alternative management approaches for by-products. In our case, we assessed the potential influence of prolonged carbon storage in durable products. Although the Energy+ and Material scenarios might appear unlikely, we intentionally included them in our analysis to estimate the potential carbon removal or emissions in the event of extreme socio-economic conditions.

3 | RESULTS

3.1 | HWP CO₂ emissions-removals

In the simulation, the net CO₂ emissions and removals associated with the use of HWP under different

TABLE 2 Scenarios summary. On the left side the name of the scenario and on the right side the characteristics.

Name	Features
Business as usual	Constant harvest, constant allocation values
Half-lives	Half-lives values increased by 10%
Cascade	+20% points recycled paper +20% points post-consumer wood
Material	+20% points recycled paper +20% points post-consumer wood −50% points wood to Energy +50% points wood to material
Energy	All by-products and post-consumer wood to bioenergy
Energy+	All by-products and post-consumer wood to bioenergy −50% points wood to material +50% point wood to Energy

TABLE 3 Net CO₂ cumulative emissions/removals of harvested wood product (HWP) per scenario per country. The values are in Mt CO₂. Negative values represent CO₂ removals while positive ones are emissions.

A	CO ₂ cumulative emission/removals HWP (Mt CO ₂) 2020–2050					
	Business as usual	Half-life	Cascade	Material	Energy	Energy+
Germany	−182.3	−249.3	−329.1	−502.4	54.3	351.4
France	−52.3	−78.4	−96.6	−290.6	−4.6	80.2
Finland	−44.7	−52.9	−50.8	−115.6	−32.8	6.2
Spain	−42.4	−58.8	−89.1	−118.3	−5.5	76.7

scenarios were estimated for the four case studies. Those estimations were based on the modelling exercise and were dependent on both the products utilisation along the chain and the end-use (e.g. recovering process). To analyse the effects of different scenarios on HWP pools through time, we summed the yearly amount CO₂ emissions/removals of HWP, and we compared it with the BAU scenario. In this paper we use negative values to represent CO₂ removals while positive ones are CO₂ emissions (Table 3).

In the GHG inventory relative to 2020, countries reported a HWP contribution of −8.6 Mt CO₂ (Germany), −1.3 CO₂ Mt (Finland), −0.8 CO₂ Mt (France) and −1.6 Mt CO₂ (Spain). The model output for the same year was −8.6 Mt CO₂ for Germany, −2.0 Mt CO₂ for Finland, −2.2 Mt CO₂ for France and −2.1 Mt CO₂ for Spain (Figure 3, historical scenario). Overall, the model seems to follow the general trend reported in the country statistics. The discrepancy between model output and GHG inventory is rooted in the difference in C stock accounting approach between these two sets of values (discussion paragraph).

The application of the scenarios had different effects between countries, but we can identify recurrent patterns. In all the simulations the Material scenario (green line) showed the lowest CO₂ emissions. More in details, for the period 2020–2050 the CO₂ emissions decreased by 456%, 158%, 176% and 179% respectively for France, Finland, Germany and Spain compared to Business as Usual (BAU; i.e. respectively −9.7, −3.9, −16.7, −3.9 Mt CO₂ per year). On the other side, for the Energy+ scenario (bordeaux line) CO₂ emissions remarkable increased. For the same period, emissions of CO₂ increased by +293% for Germany, +253% for France, +114% for Finland and +281% for Spain, respectively, compared to the baseline of each country.

The variations between the BAU scenario and the cascade scenarios (blue line) are less extreme. For all the countries, we had a decrease of the CO₂ emissions. The country which showed the highest emissions reduction for this scenario is Spain (110%) followed by France (85%), Germany (80%) and Finland (14%).

3.2 | Gross bioenergy and wood oxidation CO₂ emissions

Regarding bioenergy and wood oxidation, in the BAU scenario for the period 2020–2050 we calculated a cumulative gross emission of about 2364 Mt CO₂ for Germany, 1512 for France, 1783 for Finland and 565 for Spain. These estimations of gross emissions do not include the sink from the forest. From this baseline, the material scenario reported a notable emissions reduction which is estimated to be 22% for Germany, 16% for France, 13% for Spain and 9% for Finland. When Energy+ scenario was employed, the emission of CO₂ raised by 11% for Germany, 13% France, 38% for Finland and 17% for Spain respect to BAU (Table 4). In the cascade scenario we had a reduction in the emissions for all the countries except Finland which recorded a marginal increase respect to BAU. Moreover, increasing the product lifetime had a negligible impact on Finland while having only a minor impact on Germany and Spain (−3% CO₂ emission compared to BAU). Finally, for France we found that the gross emissions for bioenergy and wood oxidation were lower in the half-life scenario (1376 Mt CO₂) than in the cascade one (1462 Mt CO₂).

4 | DISCUSSION

This study shows that, under the assumption that the wood utilisation has the ability to change, the HWP C stock can be increased significantly in the short-medium term by prioritising the use of wood for material purposes while maintaining constant harvest.

The material scenario has the highest mitigation benefits in all the case studies. This is illustrated in Figure 3, representing the C stock change (converted to CO₂) in HWP for each scenario and where the zero line represents the equilibrium between the CO₂ removals and emissions. For the material scenario, values are significantly below the zero line, indicating a considerable increase in the carbon stock of HWP, surpassing even the growth observed in the BAU scenario. This is because, under this scenario, most of the roundwood is allocated to sawnwood, which is assumed to have a longer half-life value. Products with longer half-life may retain carbon for a longer time and thus postpone the release of CO₂ into the atmosphere. On the contrary, bioenergy has a very short half-life value, hence it does not contribute to increase the C stock in HWP. Disregarding the substitution effect in the energy sector, the amount of C allocated to bioenergy leads to a loss from the HWP C stock compared to the BAU scenario, causing an additional direct CO₂ emission to the atmosphere. In Figure 3, this is particularly evident in the positive values of the Energy+ scenario, where a considerable portion of wood is allocated to bioenergy.

The initialisation of the different scenarios and assumed sudden implementation is responsible for the discontinuity at the beginning of the scenario simulation (Figure 3). After 2040, the C stock levels off and tends to zero at the end of the time series (2050). As also found by Pilli et al. (2015), all the scenarios tend to saturate (i.e. to approach zero) when we apply constant harvest. In fact, as soon as the inflow of wood into the HWP pool is less than the year before, the pool starts to deplete, due to decay of the C stock. The material and cascade scenario show that it is possible to increase the C stored in HWP pool for at least the duration of the simulation period while keeping

TABLE 4 CO₂ cumulative gross emissions over 2020–2050 from bioenergy and wood oxidation in Mt of CO₂ ignoring forest sink (a). Relative difference in percentage between baseline (BAU) and other scenarios (b).

A	CO ₂ cumulative gross emission bioenergy and wood oxidation without substitution (Mt CO ₂)					
	BAU	Half-life	Cascade	Material	Energy	Energy+
Germany	2364	2303	2097	1850	2267	2621
France	1512	1376	1462	1265	1587	1709
Finland	1783	1776	1792	1626	1892	2461
Spain	565	549	519	493	599	660
B	Relative difference in % between baseline (BAU) and other scenarios					
	BAU	Half-lives	Cascade	Material	Energy	Energy+
Germany	-	−2.6	−11.3	−21.8	−4.1	10.8
France	-	−9.0	−3.3	−16.4	5.0	13.0
Finland	-	−0.4	0.5	−8.8	6.1	38.0
Spain	-	−2.7	−8.1	−12.8	6.0	16.8

Abbreviation: BAU, business as usual.

harvest constant by redirecting the wood initially allocated to energy to the material uses. We chose to maintain a constant harvest level to emphasise the impact of different HWP portfolios. However, it is worth noting that the utilisation of various portfolios may entail alterations in the log/pulpwood ratio within roundwood harvesting. This could potentially influence forest management and subsequently affect the carbon sink within the forest ecosystem.

The scenarios show a similar trend but the magnitude of the effects on the national carbon stocks differ greatly between countries because the forest sector in each is very different. When we compare the C stock change between countries for the same scenario, we find a major C stock increase for Germany and Spain but a relatively small one for Finland. The difference in magnitude is caused by the present-day wood utilisation path. For example, the cascading scenario produces small differences for Finland mostly for two reasons. First, Finland already has a high paper recycling rate, so the recycling shares could not be increased much. Second, the panel production is a small part of the sector and thus the additional input to panels industry does not have a large effect.

In the half-life scenario, the increase of 10% of half-life values had in all the countries a corresponding increase in the C stock. What is more relevant is that, at the same time, the C oxidation decreased on average by 5% with respect to the baseline due to the delay in the wood degradation. Concurrently, the extension of the product life-span induced a delay in the wood availability for bioenergy. The cumulative effects are particularly evident for France where in the period 2020–2050 the emissions are reduced by 50% (Table 5).

The historic scenario represents the application of the model to official data in GHG inventories. The mismatch between model output and GHG inventory is rooted in the difference in C stock accounting approach between these two sets of values (Figure 3). For the model C stock calculation, we used a *stock change* approach instead of the *production* one commonly used in country reports. We used the *stock change* approach since it includes the import and

excludes the export resulting in a more realistic representation of the amount of carbon actually retained inside the country's borders. The exclusion of the export, from the C stock calculation, has significant effect, especially in countries with strong export (i.e. Finland).

For the cascade scenario we assumed high recycling rates, although two important limitations to recycling needs to be mentioned: First, Finland already has reached a high paper recovery rate, so we did not increase it. Second, we assumed that more wood could be recycled under the assumption that attention is put to reducing the hazardous compounds used in the wood production chain. Nowadays, almost 50% of recycled wood is directly burned (Bais-Moleman et al., 2018; Van Benthem et al., 2007). The remaining half is almost all used for panels. More in detail, from the total raw material used in the panel production, 31% consists of woody industrial by-products, 48% are fresh raw materials and only 21% is post-consumer wood (EPF, 2023). It was shown however that these limitations can be overcome considerably by efficient waste wood management including material recycling, in particular for high-quality wooden beams (Mehr et al., 2018).

In the Material scenario, we considered that 50% of the initial amount allotted to bioenergy may be utilised in the sawmill sector instead. The total use of woody biomass from all sources in the EU-27 was 947Mm³ in 2017. Of this total, 45% (424Mm³) was used for energy, while 55% (523Mm³) was used for material (Camia et al., 2018). In the same year, the non-coniferous roundwood was 163Mm³ of which 83Mm³ was fuelwood (FAOSTAT, 2023). The hardwood industry and by-products utilisations are undeveloped, especially in central Europe if compared with the softwood (Teischinger, 2017). For example, the German timber industry uses 85% softwood, 13% hardwood and 2% tropical wood (Krtschil et al., 2022). In addition, stand species diversification due to the application of *climate-smart forestry* strategies will also result in a reduction of softwood produced and an increase in hardwood (Gregor et al., 2022). With this Material scenario, we want to show the potential added value of innovative hardwood utilisation which currently is underestimated within the forest-based sector.

TABLE 5 Relative difference in percentage between baseline (BAU) and the other scenarios. A minus percentage meaning an additional sink.

B	CO ₂ cumulative emission/removals harvested wood product compared with BAU (%)					
	BAU	Half-life	Cascade	Material	Energy	Energy+
Germany	-	-37	-80	-176	130	293
France	-	-50	-85	-456	91	253
Finland	-	-18	-14	-158	27	114
Spain	-	-39	-110	-179	87	281

Abbreviation: BAU, business as usual.

Although wood industry technologies are improving (e.g. CLT, Espinoza & Buehlmann, 2018; Verkerk et al., 2021) the use of different types of tree species and of lower quality, assume that large amount of fuelwood can actually be used for material purposes, which is questionable. Finally, the fuelwood saved from burning should ideally be substituted by other renewable energies for the generation of heat and power. Although the use of clean energy sources has grown a lot in the last years (Matuszewska-Janica et al., 2021), it might not be fast enough to cover the gap of a rapid decrease in fuelwood utilisation.

These findings broadly support the results of other studies in this area. For example, at the EU level cascading wood utilisation returned an increase of C stored in HWP from 34 Mt CO₂ eq to 40 Mt CO₂ eq, in the period 2010–2030 (Rüter et al., 2016). Others found a reduction of 52% of CO₂ emission (35 Mt CO₂ -eq year⁻¹) compared to the reference scenario, when the recycling rates of post-consumer wood and paper were increased (Bais-Moleman et al., 2018). A similar study estimated an increase of 5 Mt of CO₂ year⁻¹ when average HWP lifespans were increased by 19.54% or if recycling rates were raised by 20.92% for the period 2017–2030 (Brunet-Navarro et al., 2017). Mehr et al. (2018) found that future Swiss wood utilisation can be further improved in terms of environmental impact by the implementation of wood cascading. In addition, they found that waste wood processing efficiency and wood storage effects were the most important driving factors for the environmental impact of wood use scenarios. A recent study also confirmed our results that shifting secondary wood flows e.g. industrial side streams and end-of-life wood-based products from energy uses to material uses, results in increased climate benefits (Kunttu, 2020). We also found that the level of carbon stored in HWP can be increased by changing the wood assortment structure while maintaining the same level of volume felled, which is consistent with existing literature (Parobek et al., 2019; Pilli et al., 2015).

In analysing the results, the following limitations and assumptions should be taken into account. First, the model is based on a MFA that includes some data gaps. Although we have made an effort to gather all the information to close the wood flows across the countries analysed, some data gaps remain. In some processes, such as industrial residues (Figure 1), the sum of the input/output volumes were not corresponding. In this analysis, we accepted a 5% tolerance for the unbalanced processes. When this threshold was exceeded, it was indicated in the diagrams with a red mark (Figure 2; Appendix A). Most of the unbalanced processes are associated with the recovery processes and industrial residues. These gaps are probably caused by the discrepancy between reported consumption and sources of woody

biomass. In a similar study at EU level, the energy sector has been recognised as the primarily responsible for this discrepancy (Jonsson et al., 2021), which also applies to our situation where gaps were found in all of the countries mainly for industrial residues and recovering processes.

Second, the model framework is based on a single year MFA (2017), and most likely it will not represent the average wood material flow for the late 1990 and early 2000. Although the allocation of raw material input to the different commodities seems relatively stable through time, this may not be the case for the recycling processes.

Third, the way the cascade scenario approach has been implemented in other studies may have led to an overestimation of the C stock in the HWP pool. Some studies erroneously allocate recycled wood to the same product categories, which created infinite loops that can lead to an overestimation of the carbon stock in wood products (Brunet-Navarro et al., 2018). We believe that the “infinite loop” problem has a small effect in our calculations since we followed the downcycling process, where only a part of the recovered wood is redirected back to the system and always for a lower wood class utilisation (i.e. sawnwood to panels, panels to energy).

Four, in this study we excluded the landfills as carbon pools. At EU level, the amount of wood waste allocated to the landfill decreased from 710,000 tons in 2010 to 130,000 tons in 2020 (Eurostat, 2023). Although the statistics on wood waste generation and treatment are still very scattered, we assume that only a small amount of wood waste is sent to landfills and we expect that this percentage will continue to decline over the next years.

Finally, this study does not estimate the potential climate benefits of wood material and energy substitution (Sathre & O'Connor, 2010b), also due to the complexity and the uncertainty of the assumptions associated with these estimates (Hurmekoski et al., 2021). This omission may alter the market dynamics between different sectors, for example if the use of wood for short-lived products or energy is reduced, probably some other material or energy carrier is used to fill the gap in demand, which reduces the benefit of changing product portfolios. For many of the short-lived products, such as textiles or packaging, the substitution impact can be greater than for long-lived products, so the overall net climate effect of changes in the product portfolios is more complex than presented here.

5 | CONCLUSIONS

The climate change mitigation benefits of HWP vary greatly according to the use of harvested wood along the

wood chains in all the forest industry sectors. This study used a consistent methodology to determine, for four EU nations, the carbon benefits resulting from alternative uses of wood products, involving a constant input of harvest but different shares of material and energy use and different proportions of wood cascading and recycling.

Our results show that, in all scenarios, the carbon stored in the HWP tends to reach an equilibrium in a few decades, with no additional mitigation benefits. By contrast, a significant mitigation effect arises when more wood is employed for material uses, particularly for construction purposes. For the simulation period (2020–2050), the scenario with the greater allocation to material use leads to a net HWP CO₂ removals of −502 Mt CO₂ for Germany, −290 Mt CO₂ for France, −118 Mt CO₂ for Spain and −116 Mt CO₂ for Finland. Furthermore, we found potential divergences in mitigation potentials based on the nuanced characteristics of the individual national wood industry. Countries that use a large share of fuelwood have the highest potential to increase the carbon stored in HWP, under the assumption that the wood sector has the ability to change toward a greater use of wood for materials. Both the energy scenarios show an evident increase in CO₂ emissions for most of the case studies, which means that the HWP pool loses carbon. In general, we found that most of the case studies already use the by-products efficiently, while the recovery process of post-consumer wood can be increased. However, data on recovered wood were limited and more research is needed to increase the understanding of this sector.

In conclusion, to increase the carbon stored HWP, while maintaining the same level of volume felled, harvested wood should be increasingly allocated to a material use and in particular to long-lived products. Furthermore, if HWP mitigation strategies are designed according to the national wood chain characteristics, they can achieve greater climate benefits. However, prioritizing material use and long-lived products may generate a demand gap for energy carriers and short-lived products, whose climate impact depends on the materials that fill this gap, if any.

The methods and the results on HWP carbon storage from our study may contribute to future and broader assessments of the overall forest-sector mitigation benefits, which should involve analyses of both material and energy substitution and assess markets dynamics between different sectors.

AUTHOR CONTRIBUTIONS

Nicola Bozzolan: Formal analysis; investigation; methodology; project administration; visualization; writing – original draft. **Gert-Jan Nabuurs:** Resources; software; supervision; validation; writing – review and editing.

Frits Mohren: Conceptualization; data curation; methodology; supervision; writing – review and editing. **Giacomo Grassi:** Conceptualization; methodology; resources; supervision; validation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

All the authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data sources supporting the conclusions of this article are described within the article itself. Raw data and additional information can be found in the public repository (<https://doi.org/10.5061/dryad.vdncjsz1t>). For any further questions, please contact the corresponding author.

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REFERENCES

- Avitabile, V., Baldoni, E., Baruth, B., Bausano, G., Boysen-Urban, K., Caldeira Camia, A., Cazzaniga, N., Ceccherini, G., De Laurentiis, V., Doerner, H., Giuntoli, J., Gras, M., Guillen Garcia, J., Gurria, P., Hassegawa, M., Jasinevicius, G., Jonsson, R., Konrad, C., Kupschus, S., ... Patani, S. P. Z. G. (2023). *Biomass production, supply, uses and flows in the European Union*. <https://doi.org/10.2760/484748>
- Bais-Moleman, A. L., Sikkema, R., Vis, M., Reumerman, P., Theurl, M. C., & Erb, K. H. (2018). Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. *Journal of Cleaner Production*, 172, 3942–3954. <https://doi.org/10.1016/j.jclepro.2017.04.153>

- Brunet-Navarro, P., Jochheim, H., Kroiher, F., & Muys, B. (2018). Effect of cascade use on the carbon balance of the German and European wood sectors. *Journal of Cleaner Production*, 170, 137–146. <https://doi.org/10.1016/j.jclepro.2017.09.135>
- Brunet-Navarro, P., Jochheim, H., & Muys, B. (2016). Modelling carbon stocks and fluxes in the wood product sector: a comparative review. *Global Change Biology*, 22(7), 2555–2569. <https://doi.org/10.1111/gcb.13235>
- Brunet-Navarro, P., Jochheim, H., & Muys, B. (2017). The effect of increasing lifespan and recycling rate on carbon storage in wood products from theoretical model to application for the European wood sector. *Mitigation and Adaptation Strategies for Global Change*, 22(8), 1193–1205. <https://doi.org/10.1007/s11027-016-9722-z>
- Budzinski, M., Bezama, A., & Thrän, D. (2020). Estimating the potentials for reducing the impacts on climate change by increasing the cascade use and extending the lifetime of wood products in Germany. *Resources, Conservation and Recycling: X*, 6, 2–4. <https://doi.org/10.1016/j.rcrx.2020.100034>
- Buongiorno, J. (2018). On the accuracy of international forest product statistics. *Forestry*, 91(5), 541–551. <https://doi.org/10.1093/forestry/cpy025>
- Camia, A., Rober, N., Jonsson, R., Pilli, R., Garcia-Condado, S., Lopez-Lozano, R., van der Velde, M., Ronzon, T., Gurria, P., M'Barek, R., Tamosiunas, S., Fiore, G., Araujo, R., Hoepffner, N., Marelli, L., & Giuntoli, J. (2018). *Biomass production, supply, uses and flows in the European Union. First results from an integrated assessment*. <https://doi.org/10.2760/181536>
- Churkina, G., Organschi, A., Rey, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, 3(4), 269–276. <https://doi.org/10.1038/s41893-019-0462-4>
- EEA. (2022). *Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022*. Annual report (issue May). <https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-1>
- Eggers, T. (2002). *The impacts of manufacturing and utilisation of wood products on the European carbon budget*. European Forest Institute Internal Report, 2002(9), 90.
- EPF. (2023). *European Panel Federation*. <https://europanel.org/issues/sustainability/>
- Espinoza, O., & Buehlmann, U. (2018). Cross-laminated timber in the USA: Opportunity for hardwoods? *Current Forestry Reports*, 4(1), 1–12. <https://doi.org/10.1007/s40725-018-0071-x>
- Eurostat. (2023). *Eurostat*. eurostat.
- FAO. (2018). *FAOSTAT*. <http://www.fao.org/faostat/en>
- FAOSTAT. (2023). *Food and Agriculture Organization of the United Nations*. <https://www.fao.org/faostat/en/#data/FO>
- GitarSKIY, M. L. (2019). The refinement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories. *Fundamental and Applied Climatology*, 2, 5–13. <https://doi.org/10.21513/0207-2564-2019-2-05-13>
- Gregor, K., Knoke, T., Krause, A., Rey, C. P. O., Lindeskog, M., Papastefanou, P., Smith, B., Lamsø, A. S., & Rammig, A. (2022). Trade-offs for climate-smart forestry in Europe under uncertain future climate. *Earth's Future*, 10(9), 1–25. <https://doi.org/10.1029/2022EF002796>
- Hurmekoski, E., Smyth, C. E., Stern, T., Verkerk, P. J., & Asada, R. (2021). Substitution impacts of wood use at the market level: A systematic review. *Environmental Research Letters*, 16(12), 8–12. <https://doi.org/10.1088/1748-9326/ac386f>
- Jasinevičius, G., Lindner, M., Pingoud, K., & Tykkyläinen, M. (2015). Review of models for carbon accounting in harvested wood products. *International Wood Products Journal*, 6(4), 198–212. <https://doi.org/10.1080/20426445.2015.1104078>
- Jasinevičius, G., Lindner, M., Verkerk, P. J., & Aleinikovas, M. (2017). Assessing impacts of wood utilisation scenarios for a Lithuanian bioeconomy: Impacts on carbon in forests and harvested wood products and on the socio-economic performance of the forest-based sector. *Forests*, 8(4), 198–204. <https://doi.org/10.3390/f8040133>
- Johnston, C. M. T., & Radeloff, V. C. (2019). Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences of the United States of America*, 116(29), 14526–14531. <https://doi.org/10.1073/pnas.1904231116>
- Jonsson, R., Cazzaniga, N. E., Camia, A., & Mubareka, S. (2021). *Analysis of wood resource balance gaps for the EU*. <https://doi.org/10.2760/417678>
- Kallio, A. M. I., & Solberg, B. (2018). On the reliability of international forest sector statistics: Problems and needs for improvements. *Forests*, 8(2), 1–17. <https://doi.org/10.3390/f9070407>
- Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G. J., Eggers, T., Lapveteläinen, T., & Kaipainen, T. (2003). Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. *Forest Policy and Economics*, 5(2), 141–155. [https://doi.org/10.1016/S1389-9341\(03\)00021-2](https://doi.org/10.1016/S1389-9341(03)00021-2)
- Krtschil, A., Orozco, L., Bechert, S., Jakob, H., Amtsberg, F., Chen, T., Shah, A., Menges, A., & Knippers, J. (2022). Structural development of a novel punctually supported timber building system for multi-storey construction. *Journal of Building Engineering*, 58(March), 104972. <https://doi.org/10.1016/j.job.2022.104972>
- Kunttu, J. (2020). Wood utilization scenarios and their sustainability impacts in Finland. *Dissertationes Forestales*, 2020(292), 33–43. <https://doi.org/10.14214/df.292>
- Layton, R. J., Arduin, R. H., Yazdeen, H., Pommier, R., & Sonnemann, G. (2021). Material flow analysis to evaluate supply chain evolution and management: An example focused on maritime pine in the Landes de Gascogne forest, France. *Sustainability*, 13(8), 2–8. <https://doi.org/10.3390/su13084378>
- Mair, C., & Stern, T. (2017). Cascading utilization of wood: A matter of circular economy? *Current Forestry Reports*, 3(4), 281–295. <https://doi.org/10.1007/s40725-017-0067-y>
- Mantau, U. (2010). *Input and output coefficients for the wood-based industry*. <http://data.europa.eu/89h/a1f94d36-748d-48ef-81bd-f936c64e5800>
- Mantau, U. (2015). Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. *Biomass and Bioenergy*, 79, 28–38. <https://doi.org/10.1016/j.biombioe.2014.08.013>
- Matuszewska-Janica, A., Żebrowska-Suchodolska, D., Ala-Karvia, U., & Hozer-Koćmiel, M. (2021). Changes in electricity production from renewable energy sources in the European Union countries in 2005–2019. *Energies*, 14(19), 6276.
- Mehr, J., Vadenbo, C., Steubing, B., & Hellweg, S. (2018). Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades. *Resources, Conservation & Recycling*, 131, 181–191. <https://doi.org/10.1016/j.resconrec.2017.12.026>

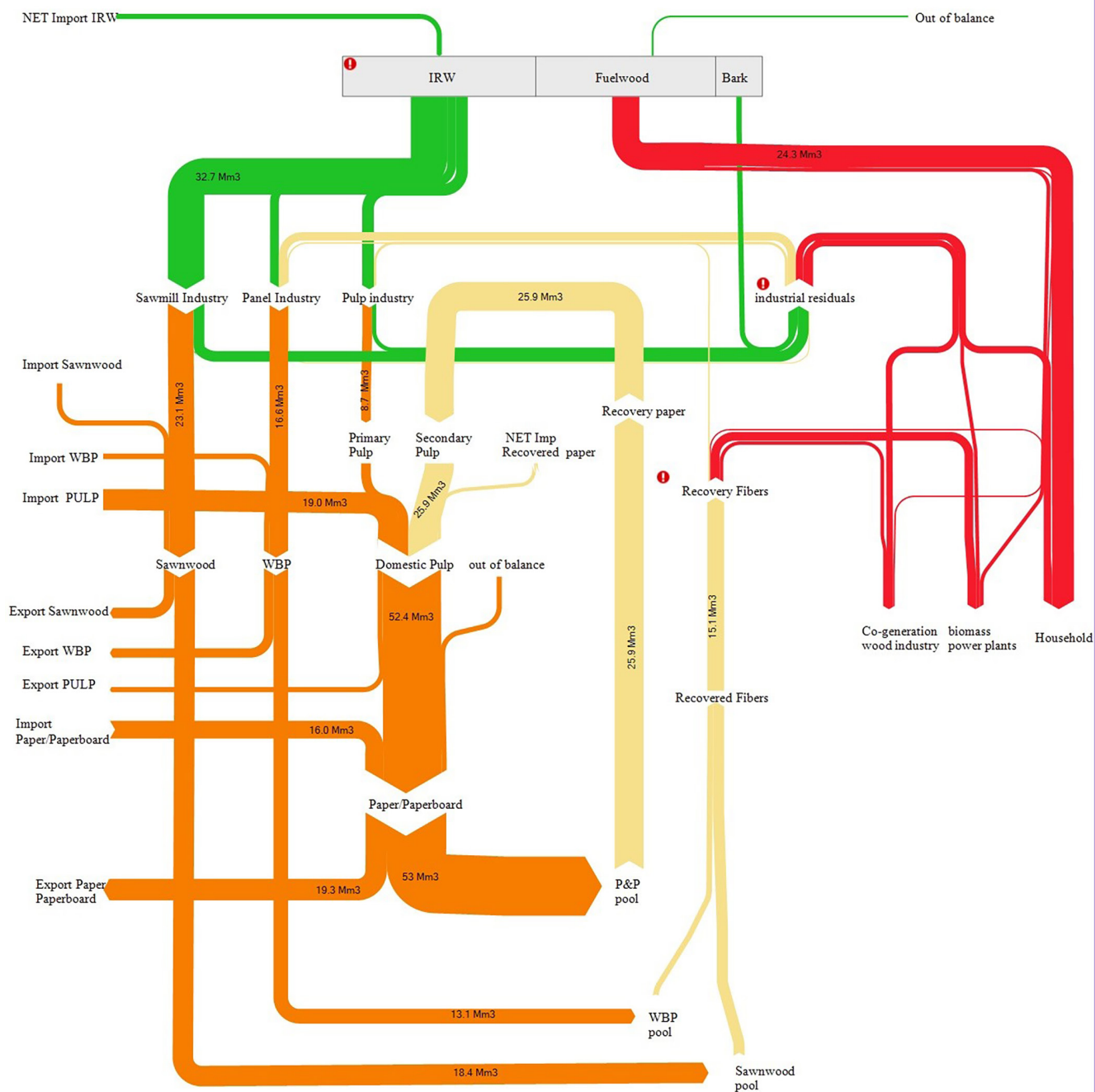
- Miteco. (2021). *Spanish database portal*. <https://www.miteco.gob.es/es/biodiversidad/estadisticas/>
- Myllyviita, T., Soimakallio, S., Judl, J., & Seppälä, J. (2021). Wood substitution potential in greenhouse gas emission reduction—review on current state and application of displacement factors. *Forest Ecosystems*, 8(1), 1–18. <https://doi.org/10.1186/s40663-021-00326-8>
- Nabuurs, G.-J., Mrabet, R., Hatab, A. A., Bustamante, M., Clark, H., Havlik, P., House, J. I., Mbow, C., Ninan, K. N., Popp, S. R., Roe, S., Sohngen, B., & Towprayoon, S. (2022). Agriculture, Forestry and Other Land Uses (AFOLU). In *IPCC, 2022: Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change. In Indonesia long term strategy for low carbon and climate resilience 2050*. <https://doi.org/10.1017/9781009157926.009>
- Parobek, J., Paluš, H., Moravčík, M., Kovalčík, M., Dzian, M., Murgaš, V., & Šimo-Svrček, S. (2019). Changes in carbon balance of harvested wood products resulting from different wood utilization scenarios. *Forests*, 10(7), 1–11. <https://doi.org/10.3390/f10070590>
- Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Kiyoto, T., & Wagner, F. (2003). *Good practice guidance for land use, land-use change and forestry*. IPCC National (Vol. 338, Issue 2). <https://doi.org/10.1016/j.crv.2014.11.004>
- Pettenella, D., Marchetti, M., Motta, R., & Vacchiano, G. (2021). Vaia storm facing the unbearable lightness of forest reporting. *Forest@*, 18(1), 1–4. <https://doi.org/10.3832/efor3733-017>
- Pilli, R., Fiorese, G., & Grassi, G. (2015). EU mitigation potential of harvested wood products. *Carbon Balance and Management*, 10(1), 6. <https://doi.org/10.1186/s13021-015-0016-7>
- Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G., & Cescatti, A. (2017). The European forest sector: Past and future carbon budget and fluxes under different management scenarios. *Biogeosciences*, 14(9), 2387–2405. <https://doi.org/10.5194/bg-14-2387-2017>
- Pingoud, K., Pohjola, J., & Valsta, L. (2009). Assessing the integrated climatic impacts of forestry and wood products. *Silva Fennica*, 10(1), 1–126.
- Rüter, S., Robert, W. M., Mattias, L., Atsushi, S., & Rehab, A. H. (2019). Harvested wood products. In *IPCC, Geneva, Switzerland. 2019 Refinement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories* (pp. 1–49). IPCC.
- Rüter, S., Werner, F., Forsell, N., Prins, C., Vial, E., & Levet, A. L. (2016). *ClimWood2030—Climate benefits of material substitution by forest biomass and harvested wood products: Perspective 2030*. Final report (no. 42). Thünen report.
- Sathre, R., & O'Connor, J. (2010a). *A synthesis of research on wood products & greenhouse gas impacts by (issue November)*. <http://lnu.diva-portal.org/smash/record.jsf?pid=diva2:455221>
- Sathre, R., & O'Connor, J. (2010b). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy*, 13(2), 104–114. <https://doi.org/10.1016/j.envsci.2009.12.005>
- Teischinger, A. (2017, September). From Forest to Wood Production—A selection of challenges and opportunities for innovative hardwood utilization. In *Proceedings of the 6th International Scientific Conference on Hardwood Processing*, Lahti, Finland (pp. 25–28).
- UNECE. (2017). *JWEE*. <https://unece.org/forests/joint-wood-energy-enquiry>
- UNECE. (2020). *Forest product conversion factors*. <https://doi.org/10.4060/ca7952en%0AThe>
- Van Benthem, M., Leek, N., Mantau, U., & Weimar, H. (2007). Markets for recovered wood in Europe; case studies for the Netherlands and Germany based on the BioXchange project. *Proc. of the 3rd European COST E31 Conf.*, 1–12.
- Verkerk, P. J., Hasegawa, M., Van Brusselen, J., Cramm, M., Chen, X., Imparato Maximo, Y., Koç, M., Lovrić, M., & Tekle Tegegne, Y. (2021). *Forest products in the global bioeconomy*. FAO, Food and Agriculture Organization of the United Nations on behalf of the Advisory Committee on Sustainable Forest-Based Industries (ACSFI). https://books.google.co.ma/books?hl=fr&lr=&id=R_FQEAAAQBAJ&oi=fnd&pg=PP2&dq=wood+tar&ots=QXMwn1vOiE&sig=l9jv2IjLFA_ysYHU159-6bocXhI&redir_esc=y#v=onepage&q=woodtar&f=false
- Vis, M., Mantau, U., & Allen, B. (2016). *CASCADES. Study on the optimised cascading use of wood: Vol. no 394/PP*. Publications Office. <https://doi.org/10.2873/827106>

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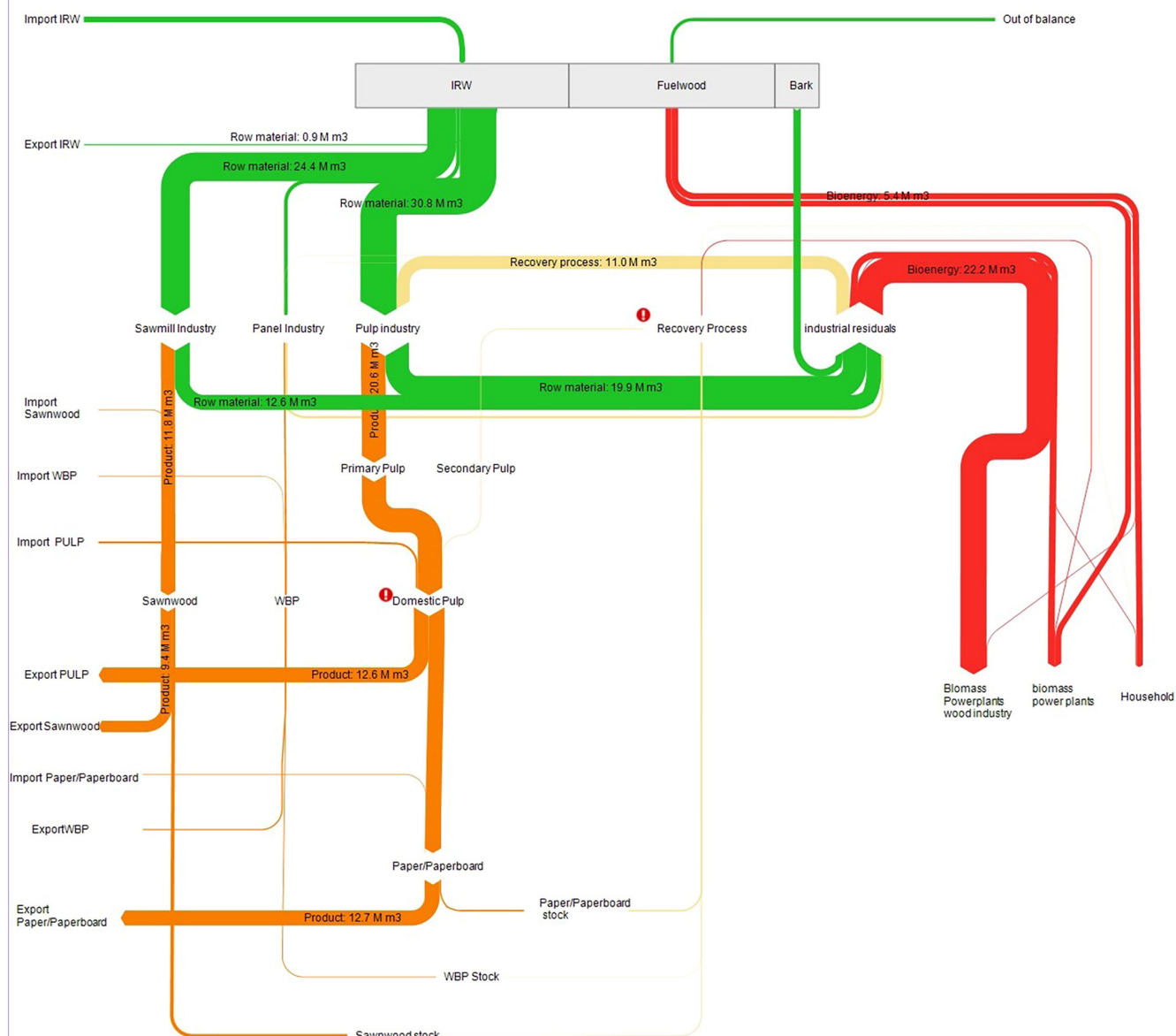
APPENDIX A

Sankey diagrams

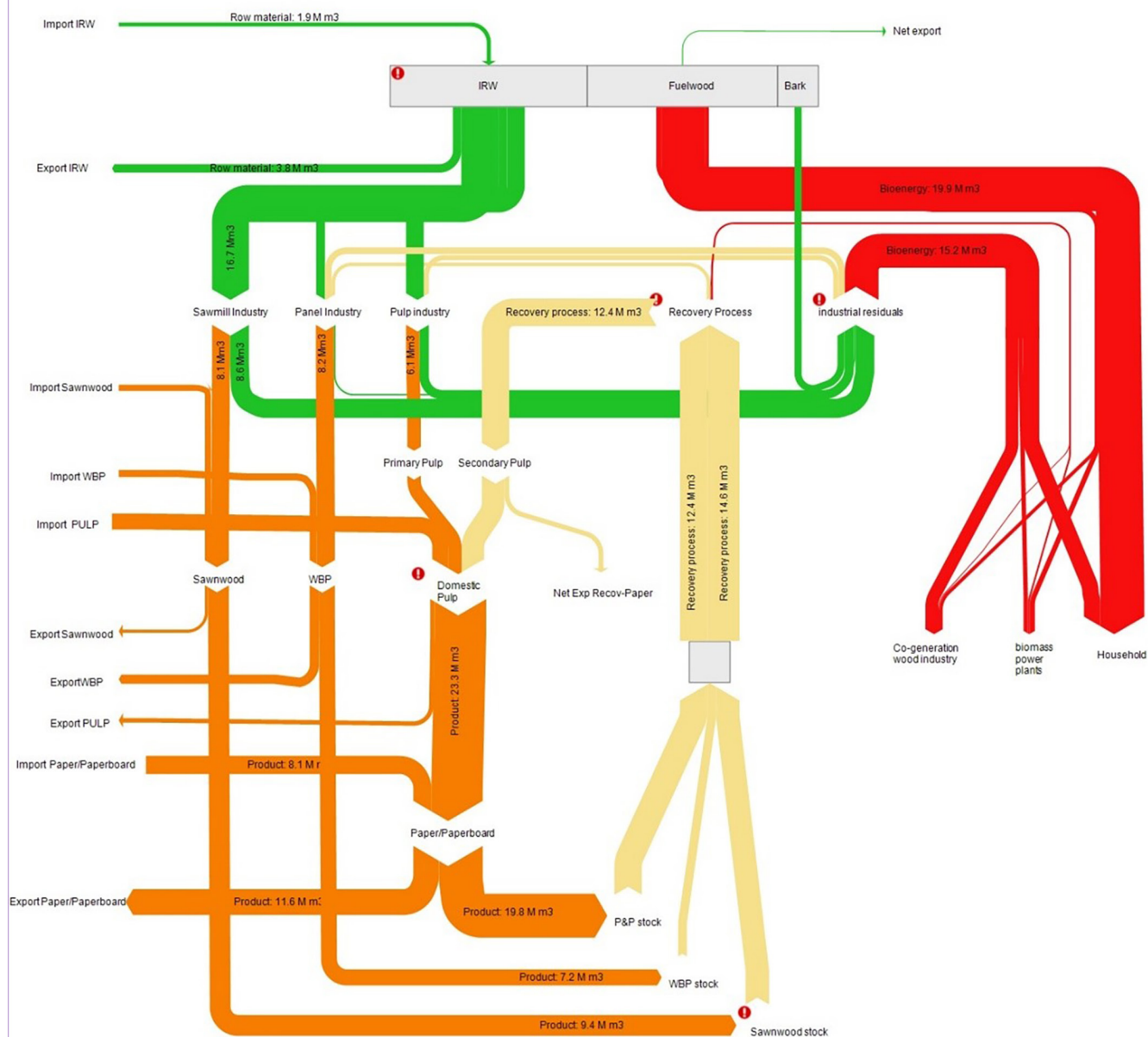
Material flow DE 2017



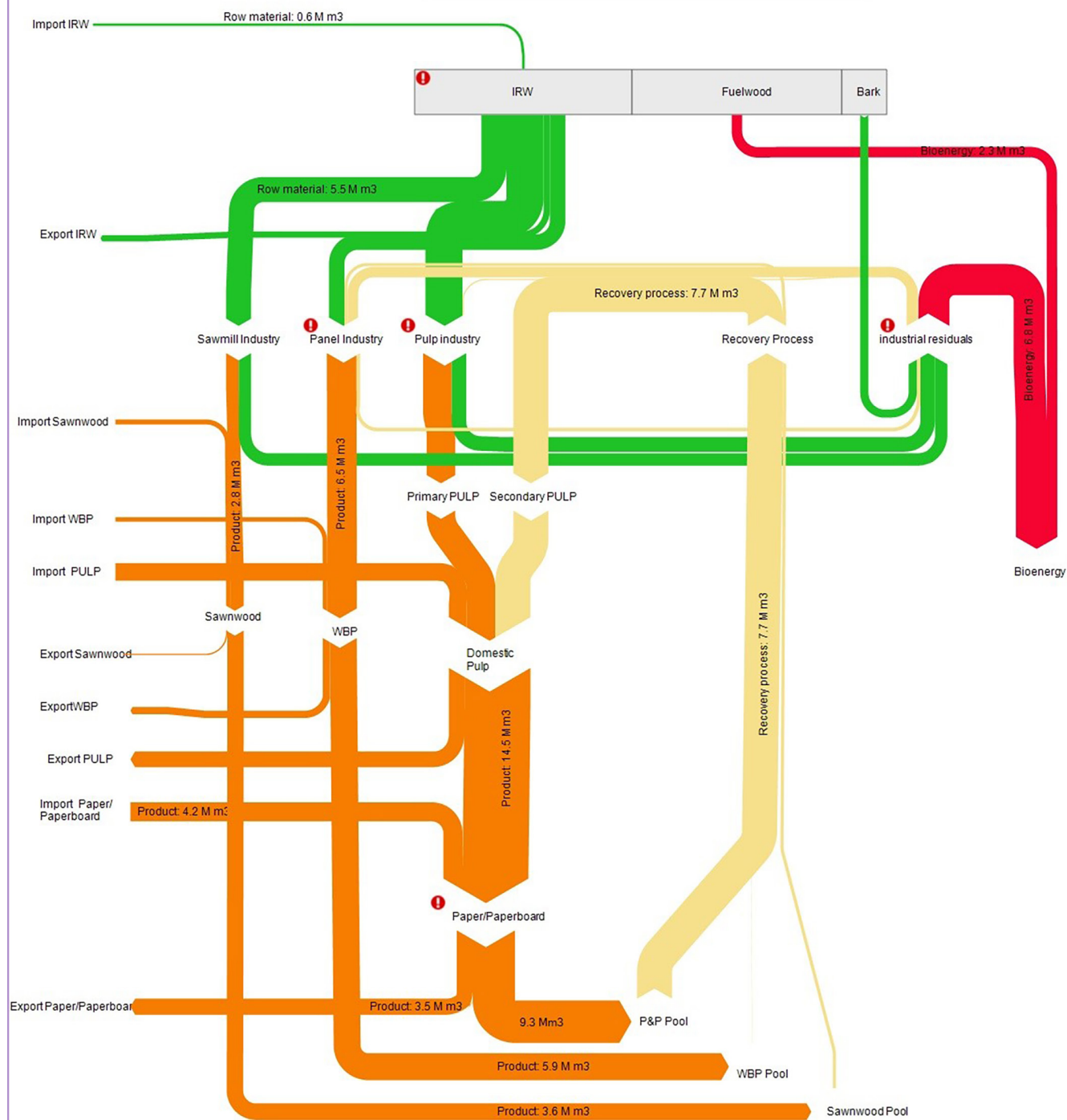
Material flow FI 2017



Material flow FR 2017



Material flow ES 2017



APPENDIX B

Values of the Sankey for Germany 2017.

Product class		Value	Unit	Year	Based on
Industrial roundwood		43.32	Mm ³ rw	2017	FAO
Import IRW		8.7	Mm ³ rw	2017	FAO
Export IRW		4.2	Mm ³ rw	2017	FAO
Net import		4.5	Mm ³ rw	2017	FAO
Sawlogs		32.7	Mm ³ rw	2017	FAO
Pulpwood		10.5	Mm ³ rw	2017	FAO
Sawmill industry residues		9.6	Mm ³ sw	2017	CAL
Sawnwood		23.1	Mm ³ sw	2017	FAO + Convers
	IMP	4.8	Mm ³ sw	2017	FAO + Convers
	EXP	9.5	Mm ³ sw	2017	FAO + Convers
	AC	18.4	Mm ³ sw	2017	FAO + Convers
Pulpwood		10.5	Mm ³ rw	2017	FAO + Convers
Wood pulp primary		8.7	Mm ³ sw	2017	FAO + Convers
	IMP	19	Mm ³ sw	2017	FAO + Convers
	EXP	4.5	Mm ³ sw	2017	FAO + Convers
Wood fibre recovery industry		41.0	Mm ³ sw	2017	CAL
	Wood	15.1	Mm ³ sw	2017	FAO + Convers
	Paper	25.9	Mm ³ sw	2017	FAO + Convers
Secondary PULP	IMP rec. Paper	8.2	Mm ³ sw	2017	FAO + Convers
Secondary PULP	EXP rec. Paper	4.9	Mm ³ sw	2017	FAO + Convers
Secondary PULP	NET IMP rec. Pap	3.3	Mm ³ sw	2017	CAL
Output domestic pulp		52.4		2017	CAL
Out of balance pulp		4.6		2017	CAL
Paper and paperboard		57	F Mm ³	2017	CAL
	IMP	16	F Mm ³	2017	CAL
	EXP	19.3	F Mm ³	2017	CAL
	APP	53.7	F Mm ³	2017	CAL
Panel industry INPUT row material		7.9	Mm ³ sw	2018	INFRO
Panel industry INPUT residues		7.5	Mm ³ sw	2018	INFRO
Wood based panel		16.6	Mm ³ sw	2017	FAO + convers
	IMP	5	Mm ³ sw	2017	FAO + convers
	EXP	8.5	Mm ³ sw	2017	FAO + convers
	AC	13.1	Mm ³ sw	2017	FAO + convers
Wood fuel		22.3	Mm ³ rw	2017	FAO
	IMP	0.4	Mm ³ rw	2017	FAO
	EXP	0.1	Mm ³ rw	2017	FAO
	Net import	0.3	Mm ³ rw	2017	FAO
Household		27.2	Mm ³	2017	JWEE
Household direct		19.5	Mm ³	2017	JWEE
Household indirect		6.4	Mm ³	2017	JWEE
Household recovered		1.2	Mm ³	2017	JWEE
U1 Power and heat		15	Mm ³	2017	JWEE
U1 Power and heat direct		3.4	Mm ³	2017	JWEE
U1 Power and heat indirect		3.2	Mm ³	2017	JWEE

APPENDIX B (Continued)

Product class	Value	Unit	Year	Based on
U1 Power and heat recovered	7.8	Mm ³	2017	JWEE
U2 Industrial	10.5	Mm ³	2017	JWEE
U2 Industrial direct	1.4	Mm ³	2017	JWEE
U2 Industrial indirect	5.7	Mm ³	2017	JWEE
U2 Industrial recycled	3.2	Mm ³	2017	JWEE
U4 Other	7	Mm ³	2017	JWEE
Bark	4.7	Mm ³ sw	2017	UNECE
Black liquor	3.7	Mm ³ sw	2018	INFRO

Sankey values for France 2017.

Product class	Value	Unit	Year	Based on
IRW	25.3	Mm ³ rw	2017	FAO
Import	1.9	Mm ³ rw	2017	FAO
Export	3.8	Mm ³ rw	2017	FAO
Bark	3.2	Mm ³ rw	2017	UNECE
Sawlogs and veneer	16.7	Mm ³ rw	2017	FAO
Residues	8.6	Mm ³	2017	CAL
Panel industry	4	Mm ³ sw	2018	INFRO
Residues	0.72	Mm ³	2018	INFRO
Pulpwood	8	Mm ³ rw	2017	FAO
Residues	4.2	Mm ³ rw	2017	CALC
Sawnwood	8.1	Mm ³ sw	2017	FAO + Conve
IMP	2.7	Mm ³ sw	2017	FAO + Conve
EXP	1.4	Mm ³ sw	2017	FAO + Conve
AC	9.4	Mm ³ sw	2017	FAO + Conve
Wood based panel	8.2	Mm ³ sw	2017	FAO + Conve
IMP	3.2	Mm ³ sw	2017	FAO + Conve
EXP	4.2	Mm ³ sw	2017	FAO + Conve
AC	7.2	Mm ³ sw	2017	FAO + Conve
Paper and paperboard	23.3	Mm ³ sw	2017	FAO + Conve
IMP	8.1	Mm ³ sw	2017	FAO + Conve
EXP	11.6	Mm ³ sw	2017	FAO + Conve
APP	19.8	Mm ³ sw	2017	FAO + Conve
Wood pulp	6.1	Mm ³ sw	2017	FAO + Conve
Import pulp	7.2	Mm ³ sw	2017	FAO + Conve
Exported	2	Mm ³ sw	2017	FAO + Conve
App con wood pulp	11.3	Mm ³ sw	2017	FAO + Conve
Wood fiber recovery industry	27	Mm ³ sw	2017	FAO + Conve
Recovered wood	14.6	Mm ³ sw	2017	FAO + Conve
Recovered paper converted	12.4	Mm ³ sw	2017	FAO + Conve
Import	0.7	Mm ³ sw	2017	FAO + Conve
Export	2.9	Mm ³ sw	2017	FAO + Conve
Wood fuel	24.9	Mm ³ rw	2017	FAO + Conve
Wood fuel Import	0.2	Mm ³ rw	2017	FAO + Conve

(Continues)

APPENDIX B (Continued)

Product class		Value	Unit	Year	Based on
	Export	0.5	Mm ³ rw	2017	FAO + Conve
Household		27.4	Mm ³ sw	2017	JWEE
Household direct		19.9	Mm ³ sw	2017	JWEE
Household indirect		7.4	Mm ³ sw	2017	JWEE
Household recovered		0.0	Mm ³ sw	2017	JWEE
U1 Power and heat		5.1	Mm ³ sw	2017	JWEE
U1 Power and heat direct		2.3	Mm ³ sw	2017	JWEE
U1 Power and heat indirect		2.0	Mm ³ sw	2017	JWEE
U1 Power and heat recovered		0.8	Mm ³ sw	2017	JWEE
U2 Industrial		7.7	Mm ³ sw	2017	JWEE
U2 Industrial direct		1.6	Mm ³ sw	2017	JWEE
U2 Industrial indirect		5.8	Mm ³ sw	2017	JWEE
U2 Industrial recycled		0.4	Mm ³ sw	2017	JWEE
U4 Other		0.0	Mm ³ sw	2017	JWEE
Panel industry wood recovery input		1.92	Mm ³ sw	2018	CALC
Panel industry residuals input		3	Mm ³ sw	2018	INFRO
Pulp industry input residuals		2.3	Mm ³ sw	2018	INFRO

Sankey values for Spain 2017.

Product class		Value	Unit	Year	Based on
IRW		14.6	Mm ³ rw	2017	FAO
	Import	0.6	Mm ³ rw	2017	FAO
	Export	1.4	Mm ³ rw	2017	FAO
Sawlogs and veneer		5.5	Mm ³ rw	2017	FAO
	Residues	2.7	Mm ³	2017	CAL
Pulpwood		8.15	Mm ³ sw	2017	FAO
	Residues	3.2	Mm ³ sw	2018	INFRO
Sawnwood		2.8	Mm ³ sw	2017	FAO + Conver
	IMP	1.1	Mm ³ sw	2017	FAO + Conver
	EXP	0.3	Mm ³ sw	2017	FAO + Conver
	AC	3.6	Mm ³ sw	2017	FAO + Conver
Wood based panel		6.5	Mm ³ sw	2017	FAO + Conver
	IMP	1	Mm ³ sw	2017	FAO + Conver
	EXP	1.6	Mm ³ sw	2017	FAO + Conver
	AC	5.9	Mm ³ sw	2017	FAO + Conver
Paper and paperboard			Mm ³ sw	2017	FAO + Conver
	IMP	4.2	Mm ³ sw	2017	FAO + Conver
	EXP	3.5	Mm ³ sw	2017	FAO + Conver
	APP	0.7	Mm ³ sw	2017	FAO + Conver
Wood pulp		6.3	Mm ³ sw	2017	FAO + Conver
Import pulp		3.9	Mm ³ sw	2017	FAO + Conver
Exported		3.4	Mm ³ sw	2017	FAO + Conver
Apparent + recovered wood pulp		14.5	Mm ³ sw	2017	FAO + Conver
Wood fibre recovery industry		-	Mm ³ sw	2017	FAO + Conver
	Recovered wood	0.7	Mm ³ sw	2017	FAO + Conver

APPENDIX B (Continued)

Product class		Value	Unit	Year	Based on
	Recovered paper converted	7.7	Mm ³ sw	2017	FAO + Conver
	Import rec paper	2.5	Mm ³ sw	2017	FAO + Conver
	Export rec pap	1.8	Mm ³ sw	2017	FAO + Conver
Wood fuel		2.3	Mm ³ rw	2017	FAO + Conver
Wood fuel	Import	-	Mm ³ rw	2017	FAO + Conver
	Export	-	Mm ³ rw	2017	FAO + Conver
Household		-	Mm ³ sw	2017	JWEE
Household direct		-	Mm ³ sw	2017	JWEE
Household indirect		-	Mm ³ sw	2017	JWEE
Household recovered		-	Mm ³ sw	2017	JWEE
U1 Power and heat		-	Mm ³ sw	2017	JWEE
U1 Power and heat direct		-	Mm ³ sw	2017	JWEE
U1 Power and heat indirect		-	Mm ³ sw	2017	JWEE
U1 Power and heat recovered		-	Mm ³ sw	2017	JWEE
U2 Industrial		-	Mm ³ sw	2017	JWEE
U2 Industrial direct		-	Mm ³ sw	2017	JWEE
U2 Industrial indirect		-	Mm ³ sw	2017	JWEE
U2 Industrial recycled		-	Mm ³ sw	2017	JWEE
U4 Other		-	Mm ³ sw	2017	JWEE
Panel industry raw wood input		3.4	Mm ³ sw	2018	INFRO
Panel industry wood recovery input		0.7	Mm ³ sw	2018	INFRO
Panel industry residuals input		2.3	Mm ³ sw	2018	INFRO
Panel industry wood recovery output		0.3	Mm ³ sw	2018	INFRO
Pulp industry input residuals		0.3	Mm ³ sw	2018	INFRO
Bark		1.8	Mm ³ sw	2017	UNECE
Black liquor		3.2	Mm ³ sw	2018	INFRO

Sankey values for Finland 2017.

Product class		Value	Unit	Year	Based on
IRW		55.3	Mm ³ rw	2017	FAO
	Import	4.8	Mm ³ rw	2017	FAO
	Export	0.9	Mm ³ rw	2017	FAO
Bark			Mm ³ sw	2017	UNECE
Sawlogs and veneer		24.4	Mm ³ rw	2017	FAO
	Residues	12.6	Mm ³	2018	CALC
Panel industry		3.2	Mm ³ sw	2018	INFRO
	Residues	1.9	Mm ³	2018	INFRO
Pulpwood		30.8	Mm ³ rw	2017	FAO + Convers
	Residues	19.9	Mm ³ sw	2018	INFRO
Sawnwood		11.8	Mm ³ sw	2017	FAO + Convers
	IMP	0.6	Mm ³ sw	2017	FAO + Convers
	EXP	9.4	Mm ³ sw	2017	FAO + Convers
	AC	3	Mm ³ sw	2017	FAO + Convers
Wood based panel		1.4	Mm ³ sw	2017	FAO + Convers
	IMP	0.4	Mm ³ sw	2017	FAO + Convers

(Continues)

APPENDIX B (Continued)

Product class		Value	Unit	Year	Based on
	EXP	1.1	Mm ³ sw	2017	FAO + Convers
	AC	0.7	Mm ³ sw	2017	FAO + Convers
Paper and paperboard		13.4	Mm ³ sw	2017	FAO + Convers
	IMP	0.5	Mm ³ sw	2017	FAO + Convers
	EXP	12.7	Mm ³ sw	2017	FAO + Convers
	APP	1.2	Mm ³ sw	2017	FAO + Convers
Wood fiber recovery industry			Mm ³ sw	2017	FAO + Convers
	Recovered wood	0.8	Mm ³ sw	2017	FAO + Convers
	Recovered paper converted	1.1	Mm ³ sw	2017	FAO + Convers
	Import	0	Mm ³ sw	2017	FAO + Convers
	Export	0	Mm ³ sw	2017	FAO + Convers
Wood fuel		7.9	Mm ³ rw	2017	FAO + Convers
Wood fuel	Import	0	Mm ³ rw	2017	FAO + Convers
	Export	0	Mm ³ rw	2017	FAO + Convers
Household		6.3	Mm ³ sw	2017	JWEE
Household direct		5.4	Mm ³ sw	2017	JWEE
Household indirect		0.6	Mm ³ sw	2017	JWEE
Household recovered		0.2	Mm ³ sw	2017	JWEE
U1 Power and heat		11.4	Mm ³ sw	2017	JWEE
U1 Power and heat direct		4.9	Mm ³ sw	2017	JWEE
U1 Power and heat indirect		5.7	Mm ³ sw	2017	JWEE
U1 Power and heat recovered		0.7	Mm ³ sw	2017	JWEE
U2 Industrial		22.8	Mm ³ sw	2017	JWEE
U2 Industrial direct		0.5	Mm ³ sw	2017	JWEE
U2 Industrial indirect		22.2	Mm ³ sw	2017	JWEE
U2 Industrial recycled		0.05	Mm ³ sw	2017	JWEE
U4 Other		0	Mm ³ sw	2017	JWEE
Panel industry wood residues output		1.9	Mm ³ sw	2018	INFRO
Panel industry wood recovery input		0.2	Mm ³ sw	2018	INFRO
Panel industry residuals input		0.1	Mm ³ sw	2018	INFRO
Panel industry wood recovery output		2	Mm ³ sw	2018	INFRO
Pulp industry input residues		11	Mm ³ sw	2018	INFRO