Effect of cascade use on the carbon balance of the German and European wood sectors

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ABSTRACT

Wood product models have often been used to estimate the carbon dynamics of wood products and evaluate their effects on the mitigation of climate change. Their increasing complexity allows for advanced analysis of industrial product conversion efficiency, product lifespan and recycling rate, although data availability for such analyses is very often problematic. In spite of the widely recognised importance of cascade chains from one wood product to another, some wood product models represent them with recycling parameters that allocate part of the recycled wood to the same product category. Consequently, the infinite repetition of these loops overestimates carbon stock.

This study analyses and benchmarks the effect on carbon stock in wood products for the German wood sector, when infinite recycling loops in wood product models are replaced by cascade chains. Different scenarios were simulated to analyse the effect of enhanced cascade chains. We estimated the carbon stock in the German wood product sector at 22.17 ± 3.82 t C per hectare of forest in the most realistic current scenario, an amount that is overestimated by 15.8% if infinite recycling loops were used instead. The deviation on the estimated carbon stock was derived from the uncertainty of allocation parameters. Then we estimated the carbon stock in the European wood product sector (EU-28) at 1231.76 t C, representing 9.16 t C per hectare of forest. The carbon stock in German wood product sector estimated for the high quality wood benchmark scenario (103.17 t C per hectare of forest) indicated that strategies to promote the development of new product designs and material technologies to enhance cascading may have the highest impact on carbon stock in the wood product sector. Studies aiming at reducing uncertainty on results are urgent, because the use of wood products is becoming an important strategy of the international community to mitigate climate change. At the same time, a correct representation of cascade use in wood product models is important because cascade practices are being promoted by governments and will probably become more common in the near future.

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1. Introduction

As trees in forests, wood products in use store carbon and can contribute to reducing the concentration of atmospheric carbon dioxide. Harvested wood products have officially been accounted as carbon sinks for the second commitment period of the Kyoto Protocol since the 17th Conference of the Parties in Durban (COP17) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2011. The changing amount of carbon stored in wood products can be included on a voluntary basis in the national inventories reported to the UNFCCC by the Parties listed in Annex II of the Kyoto Protocol. The reporting of this stock change is mandatory for the 43 Parties included in Annex I of the Kyoto Protocol. The

Paris Agreement aims at keeping the increase in the global average temperature well below 2 °C above pre-industrial levels (Article 2a) (UN, 2015). Parties that signed and ratified the Paris Agreement must undertake and communicate their efforts to achieve these goals through their respective National Determined Contributions. Such contributions must be reported periodically, representing a progression over time, and can include carbon stock in harvested wood products on a voluntary basis in a manner consistent with current UNFCCC reporting guidelines (UN, 2015). The methodologies defined in the guidelines (IPCC, 2014) estimate the amount of carbon stored in wood products using wood product models. Wood product models are also used to compare future scenarios. For instance, Fortin et al. (2012) and Karjalainen et al. (2003) analysed the effect of alternative forest management practices and climate change on carbon storage in wood products, respectively.

Multiple studies (e.g. Essel et al. (2014); Klein et al. (2013); Sokka et al. (2015); Vis et al. (2016); Werner et al. (2010)) have identified recycling as an important factor affecting the amount of carbon stored in wood products. The use and subsequent reuse of recycled woody biomass is called cascading (Fig. 1). A cascade chain defines the successive uses of a wood fibre, e.g. the successive re-use of pulp to produce recycled paper represent one cascade chain. In our definition, the energy use of the wood at the end of the cascade chain is optional, but in some other definitions of cascading it is mandatory (e.g. Essel et al. (2014)). The use of recycled wood for energy uses has no effects on the carbon stock since the average lifespan of this product use is zero years according to the IPCC Guidelines (IPCC, 2014). We do not regard the use of by-products in the main cascade chain, but they are included in a secondary one where, for instance, discarded wood chips way be used to produce particle boards.

The cascade practice is becoming more relevant, because it may save energy (greenhouse gas emission reduction) and increases the efficiency of harvested wood by using it more than once (Haberl and Geissler, 2000). In Europe, for instance, the European Commission has been promoting the cascading use of wood through the European Innovation Partnership (EIP) on Raw Materials. The EIP should develop a more sustainable supply of raw materials to European forest-based industry, and, at the same time contribute to the 2020 emission reduction objectives (European Commission, 2013).

Wood product models can be classified into two groups according to the input data used (Brunet-Navarro et al., 2016b). One group (e.g. Kohlmaier et al. (2007) or Rüter (2011)) uses production and trade data of wood commodities from statistical databases like that of the Food and Agriculture Organization of the United Nations (FAOSTAT). The other group uses estimations of the amount of harvested wood produced by dynamic forest growth models or yield tables (e.g. Profft et al. (2009) or Fortin et al. (2012)). Wood product models using databases typically exclude recycling rates to avoid double-counting, because the use of recycled wood is already included there. The models in the other group, using harvested wood as input, commonly represent industrial processes and therefore include recycling parameters. One common methodology to take recycled products into consideration is to assign a recycling rate to each product category, and then allocate recycled products, or part of them, to the same product category. Models using this methodology include, for example, CO2FIX (Schelhaas et al., 2004), LANDCARB (Krankina et al., 2012) and CAPSIS (Fortin et al., 2012). Although commonly used, this methodology creates infinite loops of recycled material being reallocated to the same product category. This can lead to overestimation of carbon storage in wood products. For example, solid wood at the end of use can be recycled to produce new particle boards, but particle boards cannot be repeatedly recycled due to a degradation of wood particles (Lykidis and Grigoriou, 2008). Thus, wood allocated to panel production should not be allocated to the same product category or any other that may create infinite loops. Instead, models should include cascade chains to direct wood fibres to successive products until achieving a final end (landfill, energy production including or not the use of ash as fertiliser). The same is true for paper fibres that can be recycled to produce new recycled paper, but this recycling loop has to be limited since paper fibres cannot be endlessly reused. In the case of Europe, paper fibres are reused 3.5 times on average (European Recovered Paper Council, 2015).

In this study, we aimed at estimating the carbon stock in harvested wood products and paper products for Germany and the related degree of overestimation by models that include infinite recycling loops. We used a method that calculates wood production from yield tables, which is why we simulated industrial processes (Section 2.1). Industrial processes were represented using three alternative data sources, which created a range of uncertainty for the results obtained. We also analysed the effects on carbon stock when cascade chains are modified. We then used the alternative method involving databases (Section 2.2) to validate our results. This second method was not only applied to Germany, but also to the whole European Union (EU-28) and afterwards compared with those from the literature.

2. Materials and methods

We applied the production approach described in the 2006 IPCC Guidelines (IPCC, 2006). This means that international trade was excluded, assuming that exported products were used inside national borders and that import did not take place. Carbon stock in German wood products was estimated for the whole of Germany and per hectare of forest using the production of harvested wood estimated from yield tables (Section 2.1). We applied the yield tables of the four most common tree species in Germany to estimate the average amount of annual harvested wood (Section 2.1.1). Industrial processes were simulated to allocate harvested wood to product categories (Section 2.1.2). Different allocation parameters were used to compare scenarios of cascade including and excluding recycling loops (Section 2.1.3). We represented uncertainty by applying a Monte Carlo simulation (Section 2.1.4). In addition, to validate the results obtained using yield tables and allocation parameters, we applied a methodology similar to the First Order Decay (Tier 2) as described by IPCC (2014) using databases to estimate carbon stock in the German and European wood product sectors (Section 2.2).

Some methodological aspects were common to both methodologies. We classified wood products in use into four categories (construction, furniture, paper and heating) each of them with a specific average lifespan (35, 25, 2 and 0 years, respectively) and recycling rate (31%, 31%, 71% and 0%, respectively). Wood product categories with an average lifespan longer than zero were defined with the
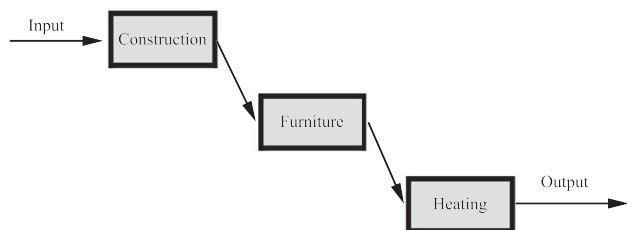

Fig. 1. The cascading concept refers to the use and reuse of wood fibres.

purpose of being close to the three categories of semi-finished products used in FAOSTAT and recommended by the IPCC (2014): sawn wood, wood-based panels, and paper and paperboard. Average lifespan values were defined following the recommendations of the IPCC (2014). We defined the recycling rate as the percentage of products (weight in t C) at the end of use being reused in product categories with average lifespans above zero years. The remaining percentage of products at the end of use was allocated to the heating category, which has no effects on wood products carbon stock (immediate emissions). Thus, we excluded landfilling assuming that the European Landfill Directive (Directive, 1990/31/EC) and the Directive on waste and repealing certain Directives (Directive, 2008/98/EC) are fully implemented. These directives will be fully implemented by 2025, but since carbon stock in wood products disposed in landfills is not accounted (IPCC, 2014) and the heating category has an average lifespan of zero years, this assumption has no consequences on carbon stock estimations. The recycling rate of construction and furniture was derived from a study by the Joint Research Centre (2009). The recycling rate of paper was extracted from the European Declaration on Paper Recycling (European Recovered Paper Council, 2015).

We assumed that products from a specific category that were produced in the same year were removed at a rate that follows a normally distributed function. The mean of the distribution is defined by the average lifespan of the product, and the standard deviation was arbitrarily defined as one third of the average lifespan. The standard deviation was uniformly defined because there is a lack of data for better approximation. We included production of different years following the distributed approach described by Marland et al. (2010), which assumes independent pools for each year of production.

2.1. Estimation of carbon stock using yield tables

A cascade chain is defined by the number of recycling loops, the utilisation of recycled fibres in new products, the average lifespan of products and their recycling rate. These combinations of cascading variables together with the production and first use of harvested wood determine the total carbon stock in the wood product sector in a given country. The effects of increasing the number of recycling loops and the use of recycled fibres in different products were analysed through six standard scenarios; one scenario including the infinite recycling loops (R) and five alternative cascading scenarios (C1-C5). The effect of increasing the lifespan and recycling rate of products was analysed by replicating these six standard scenarios with higher values of lifespan and recycling rate. Average lifespans were increased by 10%, up to 38.5, 27.5 and 2.2 years for construction, furniture and paper, respectively. Recycling rate values of construction and furniture were increased by 10% of the remaining value necessary to achieve 100% (e.g. 31+ (100-31) *0.1 = 37.9%). This formulation was applied to represent the increasing difficulty to raise recycling rate as higher is the percentage of products being recycled. The recycling rate of paper was not modified because we assumed it cannot achieve a rate of 100% due to sanitary paper use, and other paper products that are never recovered.

2.1.1. Estimation of forest yield

The annual production of harvested wood in Germany was estimated from the yield tables of Norway spruce (*Picea abies* [L.] Karst) (Wenk et al., 1984), Scots pine (*Pinus sylvestris* L.) (Lembcke, 1976), European beech (*Fagus sylvatica* L.) (Dittmar et al., 1986), and Sessile/Pedunculate oak (*Quercus petraea* (Matt.) Liebl./*Q. robur* L.) (Jüttner, 1955; cited in Schober (1975)). We used the standard stand density (1.0) and production level *M* in the yield tables of spruce, pine and beech. In the yield tables of oak, we selected "*strong management*"

from all of the available management schemes, because management has intensified in recent decades (Levers et al., 2014; Seidl et al., 2011). Annual production was averaged over the whole rotation period for each yield table.

We used the Third German National Forest Inventory (2011–2012) (BMVEL, 2011; Polley et al., 2010; Riedel et al., 2016) to calculate the percentage of forest area occupied by the four most common tree-species groups and the area per yield class for each tree species. We used the age of the forest stand and Lorey's mean height as input data for the Forest Development and Wood Supply Model (WEHAM) (Bösch and Kändler, 2016; Rock et al., 2013) to calculate the mean annual increment at age 100 years for each species. This mean annual increment value specified the number of the yield class in the yield tables for Baden-Württemberg. Then, we aggregated the plot data of each yield class with the National Forest Inventory evaluation program (Polley et al., 2010; Schmitz et al., 2008) to the forest area for whole Germany and calculated the area percentage within each yield table for Baden-Württemberg (Table 1). We used the mean annual increment at age 100 years to compare the yield tables for Baden-Württemberg with the yield tables used to estimate the production of harvested wood and estimated the area percentages for the second group of yield tables. The final production of each species used as input in the CASTLE_WPM model was calculated from the area weighted average using the production of each yield class.

Harvested wood is usually allocated to different products depending on species, stem quality, log diameter, log length, market prices and other factors. For this study, we used tree density (number of trees per hectare), frequency of forest operations (age of trees at each thinning and final cut), intensity of operations (number of removed trees) and type of operations (the relationship between diameter at breast height (DBH) of trees before thinning and the DBH of extracted trees) extracted from yield tables. There is no information on stem quality in yield tables, but we needed this to allocate harvested wood to different production lines. To solve this lack of information, DBH was used as a proxy for stem quality to allocate harvested wood when necessary. We derived the DBH of each harvested tree from yield tables assuming a normally distributed function of standing trees for each year of harvest (see Appendix A). It was assumed from this distribution function that the smallest trees (DBH smaller than 7 cm) are left in the forest because there is no commercial use of this small wood; therefore their carbon stock was not included in the wood products category. Low-quality stems were assumed to have a DBH between 7 and 25 cm. Stems with a DBH larger than 25 cm were assumed to be of high quality and allocated to different production lines. Other factors were excluded.

We used DBH (under bark) estimated from yield tables, wood density and carbon content of harvested trees to estimate the carbon stock of each tree. We assumed a bark thickness of one cm for oak, pine and spruce (Wilhelmsson et al., 2002), and 2.5 mm for beech. We used the following allometric equations to estimate the

Table 1
Percentage of forest area in Germany per yield class (mean annual increment (m^3 ha^{-1} a^{-1}) at age 100 years) for each tree species group.

Yield class	Beech (%)	Oak (%)	Spruce (%)	Pine (%)
2–4	7.78	22.66	0.00	6.53
5	9.64	15.54	1.07	9.64
6	19.57	23.35	2.20	14.61
7	20.27	18.76	2.44	17.95
8	16.51	9.64	4.12	19.84
9	11.31	5.56	6.53	16.61
10–12	14.91	4.48	35.60	14.83
13–15	0.00	0.00	26.17	0.00

volume (V) (m³) of harvested trees in Germany according to Muukkonen (2007):

For pine:

$$V = exp\left(-8.805 + 11.254 * \frac{DBH}{DBH + 9.915}\right) \qquad (1)$$

For spruce:

$$V = exp\left(-8.381 + 11.129 * \frac{DBH}{DBH + 11.079}\right) \qquad (2)$$

For beech:

$$V = exp\left(-7.087 + 10.691 * \frac{DBH}{DBH + 16.184}\right) \qquad (3)$$

For oak:

$$V = exp\left(-8.128 + 10.872 * \frac{DBH}{DBH + 11.756}\right), \qquad (4)$$

where *DBH* refers to diameter at breast height (cm). Finally, we used the wood density of each species according to Dietz (1975) (418 kg/m³ for pine, 403 kg/m³ for spruce, 578 kg/m³ for beech, and 577 kg/m³ for oak), and a carbon content of 0.5 kg per kg of wood to estimate the final values of carbon stock of each harvested tree. Results were averaged per year and per hectare.

The differentiation between coniferous and non-coniferous species was relevant to represent the wood industry. We used the Third National Forest Inventory of Germany to estimate the percentage of forest area occupied by the four most common tree-species groups (excluding forest plantations): 25.4% for spruce (*Picea* sp.), 22.3% for pine (*Pinus* sp.), 15.4% for European beech (*Fagus sylvatica* L.) and 10.4% for Sessile/Pedunculate oak (*Quercus petraea* (Matt.) Liebl./*Q. robur* L.). We assumed this proportion scaled to 100% to estimate the averaged production per hectare of forest. According to EUROSTAT, the *Forest available for wood supply* in Germany was 10.89 million hectares in 2015.

2.1.2. Representation of the wood industry

The lack of reliable data sources is one of the major problems for most wood product models (Brunet-Navarro et al., 2016b). In contrast with many other countries, the German wood-based industry can be represented by more data than just what is provided by FAOSTAT or EUROSTAT thanks to studies such as Rüter and Diederichs (2012) and Bösch et al. (2015). Using these sources, we defined the allocation parameters needed to represent the wood-based industry in Germany and to allocate harvested wood to final uses, including by-products. We ended up with three alternative allocation parameter schemes depending on the main data source used (Appendix B). The first allocation scheme was based on FAOSTAT data (Figure B.2a). For the second scheme, we exclusively used data from Bösch et al. (2015), who analysed the wood and paper flow in Germany (Figure B.2b), and therefore refer to it as the Bösch Scheme. The third scheme was a simplification of wood-based industries using four main production lines, and employing data from Rüter and Diederichs (2012), Bösch et al. (2015) and FAOSTAT (Figure B.2c).

The third scheme was the only one that provided data that could distinguish allocation parameters between small (from 7 to 25 cm DBH) and large (larger than 25 cm DBH) harvested logs. The proportion of small and large logs for each product category estimated in this third scheme was used in the other schemes to distinguish between log sizes. The second scheme provided no information to differentiate allocation parameters between coniferous and non-

coniferous. We used the proportions provided by the third scheme to allocate harvested logs according to species in the second scheme. All three schemes were used to estimate the variation of allocation of harvested wood to products in use (Fig. 2).

2.1.3. Cascading scenarios

We simulated scenarios with different uses of recycled wood keeping the initial use of harvested wood as defined in Section 2.1.2 (Fig. 2). The cascading scenarios attempt to estimate the effect on carbon stock by replacing the infinite recycling loops with one or two recycling loops, and to analyse the effect of using recycled wood by changing the use of recycled products. We created six scenarios (details in Appendix C) using the four main product categories described earlier (Table 2).

The *Re-use Scenario* (*R*) allocates recovered products to the same category of product, thus creating infinite recycling loops (Table C.1). For example, 100% of the construction wood at the end of its lifespan will either be used for construction again (31%) or for heating (69%). In this case, recycled construction wood allocated to the same category (that of construction) creates infinite recycling loops. The same is true when recycled wood from other product categories of furniture and paper is allocated to the same product category. The other scenarios replace these recycling loops by allocating recovered products to new product categories.

Cascading Scenario 1 (*C1*) allocates recycled products of construction and furniture to a new category of furniture (Table C.2). The products from the new category of furniture (like wood based panel products) were assumed to be of lower quality, and therefore were not able to be reused at the end of life. As a result, all recovered wood from the new category of furniture was assumed to be burned. Therefore, furniture products have one recycling loop in this scenario. Construction wood also has only one loop, due to the decreasing quality after end of life for this use. Recovered paper products were allocated to a new category of paper with the same characteristics of average lifespan and recycling rate. At the end of life, fibres in the new category of recycled paper were assumed to be reused once more to a new and final category of recycled paper. Afterwards, recovered paper from this third category was assumed to be burned. Thus, recycling loops for paper were limited to two. The goal of this scenario was to represent current practices as close as possible.

Cascading Scenario 2 (*C2*) allocates recycled products from construction to a new category of construction (Table C.3). Recycled products from furniture are also allocated to a new category of
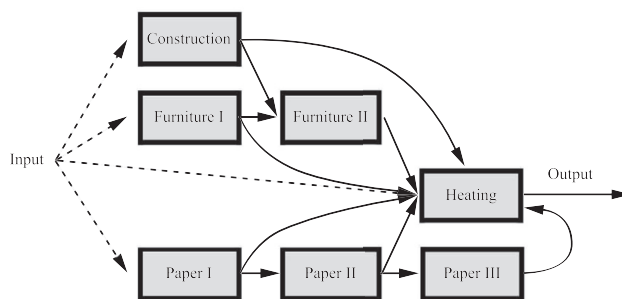
Fig. 2. Allocation of harvested wood and recycled wood. Discontinuous lines represent the allocation of harvested wood to the main categories of wood products estimated with a Monte Carlo simulation based on the three schemes defined in Section 2.1.2. Solid lines represent the allocation of recycled wood defined in Section 2.1.3. In this figure we used *Cascading scenario 1* as an example that includes one loop for furniture products and two loops for paper products.

Table 2
Description of the re-use and the five cascading scenarios. Con: Construction category; F: Furniture category; P: Paper category; R: *Re-use scenario*; C1: *Cascading scenario 1*; C2: *Cascading scenario 2*; C3: *Cascading scenario 3*; C4: *Cascading scenario 4*; C5: *Cascading scenario 5*.

Scenario	Number of loops			Allocation of recycled fibres		
	Con	F	P	Con	F	P
R	∞	∞	∞	Con	F	P
C1	1	1	2	F	F	P
C2	1	1	2	Con	F	P
C3	1	2	2	Con	F	P
C4	2	2	2	Con	F	P
C5	1	1	2	Con	Con	P

furniture as in *C1*. Recycled paper products are allocated to two new categories of paper as done in *C1*. The only difference between this scenario and *C1* is that the quality of the use of recycled construction products (like oriented strand board) does not decrease. This scenario is closer to the *R* scenario, as recycled construction and furniture products (like particleboards) are allocated to the same product category, but here the number of loops is limited to one.

Cascading Scenario 3 (*C3*) increases the number of loops for furniture to two (Table C.4). All other characteristics are the same as in *C2*. *Cascading Scenario 4* (*C4*) increases the number of loops for construction to two (Table C.5); all other characteristics are the same as in *C3*. *Cascading Scenario 5* (*C5*) is similar to *C1* with the difference that recycled construction and furniture are allocated to a new category of construction instead of a new category of furniture (Table C.6). In other words, while recycled construction wood keeps the same level of quality for use, the level of recycled furniture actually improves.

2.1.4. Benchmarking

In addition, we created two extreme scenarios (*High quality wood benchmark* and *Low quality wood benchmark*) to benchmark all cascading scenarios described in section 2.1.3. The *High quality wood benchmark* aimed at maximising carbon stock in wood products (Figure B.3a and Table 3). We did not use the previous allocation schemes described in Section 2.1.2 for this scenario. Instead, we created an idealistic scheme where harvested wood was used mainly for construction. We used realistic data to define industrial efficiency. High-quality logs (larger than 25 cm DBH) were processed mainly in sawmills (89.52% of logs) as in the Simple Scheme. The remaining 10.48% of logs were chipped. Sawmills produced sawn wood (48.5%) and chips (51.5%). As in the Simple Scheme, sawn wood was used for construction (83.59%) and for heating (16.41%). All low-quality logs were assumed to be chipped. Chips were used as raw material to produce panels (92.6%) and for heating and drying of feedstock (7.4%). Panels were used for construction (76.75%) and for heating (23.25%). We assumed that construction products could be reused up to four times including final use for heating, but during the first and second recycling processes 20% of the wood products were allocated to heating. We assumed that industries used alternative energies when not enough wood was available for drying purposes.

The aim of the *Low quality wood benchmark* was to maximize the use of wood for heating, the product with the shortest average lifespan (Figure B.3b and Table 4). No simulation was needed in this scenario because all harvested wood was used to produce heating (zero years of lifespan) and therefore carbon stock in wood products was zero.

2.1.5. Simulation

The uncertainty of the representation of the wood industry (Section 2.1.2) was addressed by applying a Monte Carlo resampling

Table 3
Allocation parameters of the *High quality wood benchmark*. Con: Construction category. H: Heating category.

Product	Small	Large	Con (i+1)	H
Con (i)	71.07	76.51	80	20
H	28.93	23.49	0	0

procedure with 2000 runs. The three schemes that were defined to allocate harvested wood to the four product categories were employed to represent the uncertainty of the allocation parameters following a normal distribution. Thus, each combination of the four tree species, the six scenarios (*R, C1-C5*) and the three sets of parameters (standard, incremented product lifespans and incremented product recycling rates) were simulated 2000 times (144,000 simulations in total). In addition, the *High quality wood benchmark* was simulated for each species and each parameter set (12 simulations). The *Low quality wood benchmark* was not simulated because all harvested wood was allocated to the Heating product category with zero years of lifespan and therefore no carbon stock. In total, 144,012 simulation runs were performed (Table 5).

Each model run had to achieve a steady state, defined as the point where carbon stock stops increasing and stabilizes. For this to occur, we must be sure that wood fibres produced in the first simulated year have been burned. Thus, all simulations covered a period of 500 years, with the exception of the *High quality wood benchmark*, which was extended to 1000 years because of the higher recycling rate. Time increments of the model were one year. We ran the six scenarios independently. Results obtained for each species were averaged with respect to the proportions of area occupied for each species. All calculations were performed using *R* software (version 3.0.1). For more information, see Appendix A, which includes the R script of the CASTLE_WPM model used in these simulations.

2.2. Estimations of carbon stock using international public databases

A different methodology was used to validate the results. In this case, the FAOSTAT database was used to estimate the quantity of wood-based products produced in Germany and Europe (EU-28) in 2015. The FAOSTAT product categories used to estimate harvested wood from forests were *Roundwood* (codes 1862 and 1963). Categories used to estimate carbon stock in wood products were *Paper and Paperboard* (code 1876), *Sawnwood* (codes 1632 and 1633), *Wood Fuel* (codes 1627 and 1628) and *Wood-Based Panels* (code 1873). We used the default conversion factors provided by the IPCC (2014) in order to transform the production values provided by FAOSTAT from m³ (Mg for the *Paper and Paperboard* category) to t C (Table B.1). For *Roundwood*, we used the same conversion factors of *Sawnwood* since both are composed by solid wood. Production in 2015 was estimated assuming an increase over 2014 of 1.54%, derived from Mantau and Saal (2010).

The time period of data available provided by FAOSTAT (54 years from 1961 to 2014) is too short to allow wood produced at the beginning of the simulation to be removed completely according to Brunet-Navarro et al. (2016a). We assumed linearly increasing

Table 4
Allocation parameters of the *Low quality wood benchmark*. H: Heating category.

Product	Small	Large
H	100	100

Table 5
Overview of the different combinations for the simulation runs.

Tree species	Allocation scheme	Cascading scenario	Variation of product characteristics
4 tree species spruce (9 yield classes), pine (12 yield classes), beech (9 yield classes) and oak (3 yield classes)	FAOSTAT Bösch Simple *High quality wood benchmark* *Low quality wood benchmark*	6 scenarios (*R, C1-C5*)	3 parameter sets (standard, increased lifespan, and increased recycling rate) Not needed

production, starting with 0 t C in 1800 until the first value provided by FAOSTAT for 1961. Missing production data for individual or multiple years in the database were linearly interpolated. The recycling rate was not considered, since FAOSTAT data already includes products produced from recycled wood like the use of post-consumer wood waste for particle board production. To estimate the average results of carbon stock per hectare of forest, we used the area of *Forests available for wood supply* for 2015 provided by EUROSTAT.

3. Results

3.1. The estimated carbon stock in Germany using yield tables

The harvested wood from German forests estimated using yield tables was on average 0.422 t C ha^{-1} year^{-1} for small logs and 1.046 t C ha^{-1} year^{-1} for large logs. Table 6 compares harvested wood for each species in the analysis. The total amount of wood harvested in Germany was estimated to be 15.982 Mt C year^{-1}.

Among the standard scenarios, Scenario *R* stored the highest amount of potential carbon in wood products in the steady state (25.68 ± 4.37 t C ha^{-1}) (Fig. 3 and Table 7). Scenario *C4*, which included two loops for furniture and construction products, resulted in the second highest amount of carbon stock (24.74 ± 4.24 t C ha^{-1}). Scenarios *C2*, *C3* and *C5* all stored similar amounts of carbon (23.11 ± 3.95, 23.71 ± 4.09, and 23.89 ± 4.14 t C ha^{-1}, respectively). The scenario with the lowest amount of carbon stock was *C1* (22.17 ± 3.82 t C ha^{-1}). The results obtained when applying higher lifespans and recycling rates were higher compared to when the standard values were used (Fig. 3, Tables 8 and 9). The increase in carbon stock for each scenario after extending product lifespans were about 10–11% higher, and after raising the recycling rate were between 4 and 11% higher.

Carbon stock in wood products under the *High quality wood benchmark* was estimated to be 103.17 t C ha^{-1} (1123.36 Mt C) for the standard scenario, 113.50 t C ha^{-1} (1235.82 Mt C) when the average lifespan was increased and 106.38 t C ha^{-1} (1158.26 Mt C) when recycling rate was raised. For the *Low quality wood benchmark*, carbon stock in wood products was 0 t C ha^{-1} (0 Mt C) for all cases.

3.2. The estimated carbon stock in the EU using international public databases

When FAOSTAT data was used as an input, the amount of carbon in harvested *Roundwood*, annual product production, and in total

wood products in use in Germany for 2015 was estimated to be 1.214 t C ha^{-1}, 1.845 t C ha^{-1} and 23.794 t C ha^{-1}, respectively. Table 10 shows the results for each EU-28 country in the analysis and the averaged results for the EU-28.

4. Discussion

This study assesses the carbon pool of the German wood product sector, and aims at calculating the effect of using cascade chains instead of infinite recycling loops. We developed a model capable of defining as many cascading steps as needed. The main difficulty we faced was to estimate the parameters needed to allocate harvested wood to actual products in use. As in most wood product model applications, we were forced to make many assumptions to estimate all the necessary data: from forest production to average lifespan and recycling rates. To complete lacking datasets, we used official recommendations when available. We selected Germany as a case study, because various studies for this country have provided more specific data than for other countries or regions. In order to validate our results and compare them with other publications, we also used alternative data sources and an alternative methodology to estimate carbon stock in the wood products of all European Union countries (EU-28).

4.1. Cascade chains versus infinite recycling loops

Of all the scenarios, including those with cascade chains (*C1-C5*), Scenario *C2* (which includes one recycling loop, where construction and furniture products are allocated to new categories of construction and furniture respectively) is the closest to Scenario *R* (the one with infinite recycling loops) in terms of the allocation of recycled wood, because these two scenarios allocate recycled products to the same product use. Comparison between Scenarios C2 and R would lead to the conclusion that the inclusion of infinite recycling loops overestimates the carbon stock in wood products by 11.1%. However, Scenario *C1* is the closest to reality, because here recycled wood is allocated to furniture, which fits with the observation that recycled wood is mainly used to for products with a medium life span (Joint Research Centre, 2009), such as furniture. Thus, overestimations due to infinite recycling loops (Scenario *R*) compared to the most realistic current scenario (*C1*) amount to 15.8% for standard values of recycling loops and lifespans, to 16.1% for longer lifespans, and to 22.8% with increased recycling rates. Consequently, carbon stock is significantly overestimated by models that include infinite recycling loops. This overestimation would become even more relevant if recycling rates were to raise in

Table 6
Estimated annual rate of harvested wood in Germany. Comparison of different species and log size (small logs have a DBH between 7 and 25 cm, large logs have a DBH larger than 25 cm). The "Average" row represents the averages weighted by area.

Species	Small logs (t C ha^{-1} year^{-1})	Large logs (t C ha^{-1} year^{-1})	Total (t C ha^{-1} year^{-1})	Total (Mt C year^{-1})
Beech	0.437	1.087	1.524	3.478
Pine	0.336	0.881	1.217	4.021
Spruce	0.548	1.323	1.871	7.040
Oak	0.275	0.662	0.937	1.444
Average	**0.422**	**1.046**	**1.468**	**15.982**
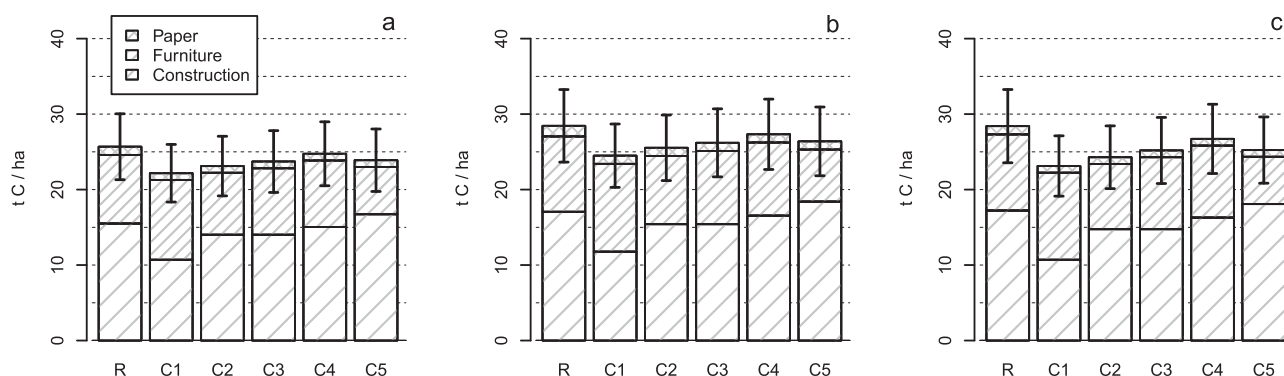
Fig. 3. Carbon stock in wood products (mean ± standard deviation) estimated using production from yield tables according to the re-use and the five cascading scenarios analysed (a) using standard values of average lifespan and recycling rate, (b) using standard values of recycling rate and increased lifespans, and (c) using standard values of average lifespan and increased recycling rates. R: *Re-use scenario*; C1: *Cascading scenario 1*; C2: *Cascading scenario 2*; C3: *Cascading scenario 3*; C4: *Cascading scenario 4*; C5: *Cascading scenario 5*.

Table 7
Carbon stock in wood products estimated using production values from yield tables under the re-use and the five cascading scenarios using standard values of average lifespan and recycling rate. sd: Standard deviation; R: *Re-use scenario*; C1: *Cascading scenario 1*; C2: *Cascading scenario 2*; C3: *Cascading scenario 3*; C4: *Cascading scenario 4*; C5: *Cascading scenario 5*; Con: Construction; F: Furniture; P: Paper.

Scenario	Con (t C ha^{-1})	F (t C ha^{-1})	P (t C ha^{-1})	Total ± sd (t C ha^{-1})	Total ± sd (Mt C)
R	15.51	9.08	1.09	25.68 ± 4.37	279.57 ± 47.55
C1	10.70	10.58	0.89	22.17 ± 3.82	241.34 ± 41.56
C2	14.02	8.21	0.89	23.11 ± 3.95	251.66 ± 42.98
C3	14.02	8.81	0.89	23.71 ± 4.09	258.21 ± 44.58
C4	15.04	8.81	0.89	24.74 ± 4.24	269.39 ± 46.13
C5	16.74	6.27	0.89	23.89 ± 4.14	260.12 ± 45.06

Table 8
Carbon stock in wood products estimated using production values from yield tables under the re-use and the five cascading scenarios using incremented values of average lifespan. sd: Standard deviation; R: *Re-use scenario*; C1: *Cascading scenario 1*; C2: *Cascading scenario 2*; C3: *Cascading scenario 3*; C4: *Cascading scenario 4*; C5: *Cascading scenario 5*; Con: Construction; F: Furniture; P: Paper.

Scenario	Con (t C ha^{-1})	F (t C ha^{-1})	P (t C ha^{-1})	Total ± sd (t C ha^{-1})	Total ± sd (Mt C)
R	17.06	9.99	1.40	28.44 ± 4.81	309.70 ± 52.33
C1	11.77	11.63	1.08	24.49 ± 4.20	266.65 ± 45.73
C2	15.42	9.03	1.08	25.53 ± 4.34	278.00 ± 47.29
C3	15.42	9.69	1.08	26.19 ± 4.51	285.21 ± 49.05
C4	16.55	9.69	1.08	27.32 ± 4.66	297.51 ± 50.75
C5	18.41	6.89	1.08	26.39 ± 4.55	287.31 ± 49.58

Table 9
Carbon stock in wood products estimated using production values from yield tables under the re-use and the five cascading scenarios using increased recycling rates. sd: Standard deviation; R: *Re-use scenario*; C1: *Cascading scenario 1*; C2: *Cascading scenario 2*; C3: *Cascading scenario 3*; C4: *Cascading scenario 4*; C5: *Cascading scenario 5*; Con: Construction; F: Paper.

Scenario	Con (t C ha^{-1})	F (t C ha^{-1})	P (t C ha^{-1})	Total ± sd (t C ha^{-1})	Total ± sd (Mt C)
R	17.23	10.09	1.09	28.41 ± 4.85	309.28 ± 52.82
C1	10.70	11.53	0.89	23.12 ± 4.00	251.78 ± 43.51
C2	14.76	8.64	0.89	24.28 ± 4.16	264.40 ± 45.24
C3	14.76	9.54	0.89	25.18 ± 4.38	274.18 ± 47.66
C4	16.29	9.54	0.89	26.72 ± 4.59	290.91 ± 49.94
C5	18.08	6.27	0.89	25.23 ± 4.39	274.74 ± 47.80

the future (Vis et al., 2016).

Obviously, the effect of removing recycling loops is smaller when the cascade chain is extended (Scenarios *C3* and *C4*). The carbon stock almost did not increase at all when an additional loop was added to medium lifespan products with low recycling rates (Scenario *C3*), but the effect was larger when the loop dealt with products with longer lifespans and higher recycling rates (Scenario *C4*). The potential of increasing carbon stock by improving cascade chains is huge when results are compared to the *High quality wood benchmark* (Fig. 4). Although the *High quality wood benchmark* is

currently idealistic, it points out how much the carbon stock in wood products could be increased by using higher proportions of harvested wood for those products with long lifespans and high recycling rates.

4.2. Increasing lifespans and recycling rates

When the lifespan of wood products was increased by 10%, carbon stock increased about 10—11% in all scenarios. On the other hand, when the recycling rate increased, carbon stock increased

Table 10
Amount of carbon harvested and stored in wood products domestically produced per hectare of productive forest (*Forest available for wood supply*) for each European country using FAOSTAT data.

Country	Forest area (million hectares)	Products Production (t C ha^{-1} year^{-1})	Products production (10^6 t C year^{-1})	Sawnwood Stock (t C ha^{-1})	Sawnwood stock (10^6 t C)	Panels stock (t C ha^{-1})	Panels stock (10^6 t C)	Paper stock (t C ha^{-1})	Paper stock (10^6 t C)	Total stock in products (t C ha^{-1})	Total stock in products (10^6 t C)
EU28	134.486	0.767	103.151	5.349	719.366	2.533	340.653	1.276	171.604	9.159	1231.757
Austria	3.339	1.787	5.967	19.744	65.925	5.526	18.451	2.681	8.952	27.952	93.332
Belgium	0.670	3.057	2.048	14.922	9.998	25.518	17.097	5.477	3.670	45.917	30.764
Bulgaria	2.213	0.572	1.266	3.083	6.823	1.758	3.890	0.259	0.573	5.101	11.289
Croatia	1.740	0.682	1.187	3.816	6.640	0.477	0.830	0.411	0.715	4.704	8.185
Cyprus	0.041	0.043	0.002	4.323	0.177	1.468	0.060	0.000	0.000	5.791	0.237
Czech Republic	2.301	0.892	2.052	12.515	28.797	3.254	7.487	0.585	1.346	16.353	37.628
Denmark	0.572	1.656	0.947	8.025	4.590	4.747	2.715	1.565	0.895	14.337	8.201
Estonia	1.994	0.548	1.093	3.878	7.733	1.071	2.136	0.066	0.132	5.015	10.000
Finland	19.465	0.461	8.973	4.022	78.288	0.542	10.550	1.033	20.107	5.597	108.946
France	16.018	0.890	14.256	4.984	79.834	2.101	33.654	0.962	15.409	8.048	128.913
Germany	10.888	1.845	20.088	12.238	133.247	7.785	84.763	3.771	41.059	23.794	259.069
Greece	3.595	0.160	0.575	0.574	2.064	1.087	3.908	0.224	0.805	1.886	6.780
Hungary	1.779	0.679	1.208	2.958	5.262	2.010	3.576	0.655	1.165	5.622	10.002
Ireland	0.632	0.783	0.495	7.826	4.946	6.683	4.224	0.158	0.100	14.668	9.270
Italy	8.216	0.757	6.220	1.903	15.635	3.642	29.923	1.961	16.112	7.506	61.669
Latvia	3.151	0.499	1.572	5.924	18.667	1.082	3.409	0.028	0.088	7.034	22.164
Lithuania	1.924	0.659	1.268	3.592	6.911	1.548	2.978	0.125	0.241	5.265	10.130
Luxemburg	0.086	2.225	0.191	11.485	0.988	23.945	2.059	0.442	0.038	35.872	3.085
Malta	0.000	–		–		–		–		–	
Netherlands	0.301	4.138	1.246	9.221	2.776	1.260	0.379	17.060	5.135	27.540	8.290
Poland	8.234	0.803	6.612	4.782	39.375	4.513	37.160	0.860	7.081	10.155	83.616
Portugal	2.088	0.746	1.558	5.973	12.472	3.916	8.177	1.778	3.712	11.667	24.361
Romania	4.627	0.904	4.183	7.109	32.893	2.518	11.651	0.147	0.680	9.774	45.224
Slovakia	1.785	0.605	1.080	5.900	10.532	1.935	3.454	0.805	1.437	8.640	15.422
Slovenia	1.139	0.846	0.964	3.604	4.105	2.384	2.715	1.138	1.296	7.126	8.117
Spain	14.711	0.342	5.031	1.605	23.611	1.619	23.817	0.801	11.784	4.025	59.212
Sweden	19.832	0.496	9.837	5.815	115.323	0.304	6.029	1.005	19.931	7.124	141.283
United Kingdom	3.144	1.227	3.858	6.307	19.829	5.966	18.757	2.612	8.212	14.885	46.798

10.6% in Scenario *R*, but only between 4.3% and 8.0% in the other scenarios, depending on the number of recycling loops. Therefore, we observe that the higher the recycling rates, the more the carbon stock becomes overestimated by models using infinite recycling loops. Notice that recycling rates of 100% are neither economical nor technically feasible.

The standard deviation estimated was about 17% of the mean value estimated (Tables 7–9). This significant variation reveals the importance of reducing uncertainty regarding allocation parameters. In the absence of more precise parameters, analysis of forest management, wood product use or changing growing circumstances through climate change creates uncertainty on the results. The same magnitude of error created will be reported when estimating carbon stock change (i.e. the difference between successive years). The carbon stock change is relevant when reporting national emissions from the Land Use, Land Use Change and Forestry sector to the UNFCCC.

4.3. Normal distribution function versus First Order Decay approach

The First Order Decay approach defined in the IPCC Guidelines and used in several studies (e.g. Dymond et al. (2016); Pilli et al. (2015); Pingoud and Wagner (2006); Rüter (2011); Sikkema et al. (2013)) uses the exponential decay function to estimate that the removal rate of wood products in use to become available slowly, depending on products' lifespan. However, we instead assumed that products from a specific category that were produced in the same year were removed at a rate that follows a normally distributed function as done in studies like Muller et al. (2004) or Brunet-Navarro et al. (2016a). The First Order Decay approach includes the single pool approach, but we included production of different years following the distributed approach. We employed the normal distribution function because it simulates that products are removed around the average lifespan. This is a more complex methodology, but simulates a more realistic behaviour than the exponential decay function which simulates that most products are removed starting from the first year after their production (Brunet-Navarro et al., 2016b).

4.4. Forest production form yield tables

We simulated forest production using yield tables that were created decades ago, but current yield and management may be different (Levers et al., 2014; Seidl et al., 2011). Other assumptions we used may also contribute to create inaccuracy in our results. For example, we only used four species to depict all forests of Germany, while they only represent 75% of the forest area, or we calculated the area covered by each yield class using a different group of yield tables (yield tables from Baden-Württemberg). The conversion factors used for transforming volume into carbon stock based on wood density and carbon content in the two methodologies (using yield tables and public databases) differs for the coniferous species by about 10% and causes some differences between employed methodologies. In spite of all these approximations, the amount of harvested wood estimated in Germany (15.98 Mt C year^{-1}) is just slightly higher than the value reported by FAOSTAT as round wood removals (12.4 Mt C year^{-1}). But, the carbon stock in wood products that we estimated using FAOSTAT production data (23.794 t C ha^{-1}) is not significantly different from the carbon stock in wood products we estimated using production from yield tables (assuming a 95% confidence interval) (Fig. 4).

4.5. Estimation of carbon stock in wood products

One problem for models that represent industrial processes is
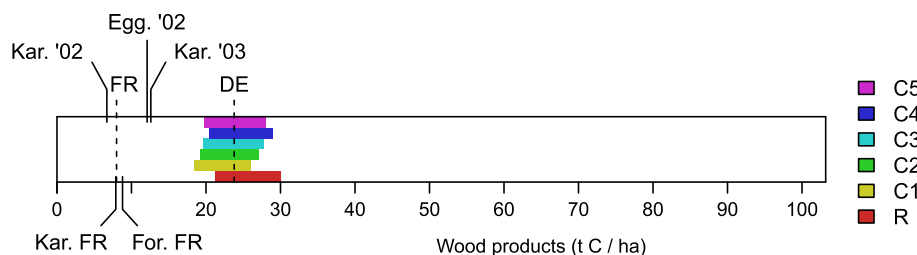
Fig. 4. Benchmarking the results of carbon stock in wood products. The lowest value represents the *Low quality wood benchmark* and the highest value represents the *High quality wood benchmark*. Rectangles represent the variability (mean ± standard deviation) of each standard cascading scenario described in Section 2.1. Dashed lines represent the carbon stock in wood products values for France (FR) and Germany (DE) using IPCC methodology (Section 2.2). Kar. '02: Carbon stock in German wood products estimated in Karjalainen et al. (2002); Kar. '03: Carbon stock in German wood products estimated in Karjalainen et al. (2003); Kar. FR: Carbon stock in French wood products estimated in Karjalainen et al. (2003); For. FR: Carbon stock in French wood products estimated in Fortin et al. (2012).

the uncertainty of the allocation parameters needed to allocate harvested wood to products in use (Brunet-Navarro et al., 2016b). Models using wood product databases avoid this problem by excluding representations of industrial processes, with negative consequences for their accuracy but improvements in terms of their precision. Additionally, these models are limited when it comes to estimating future scenarios regarding changing growing circumstances through climate change, alternative wood harvesting regimes or different uses of harvested wood.

We used other studies of the same region to corroborate our results and identified very important differences in the process (Fig. 4). A study by Karjalainen et al. (2003) calculated 12.7 t C ha^{-1} in wood products, which is almost half than our estimation for the most realistic current scenario (22.17 ± 3.82 t C ha^{-1}). A similar value (12.1 t C ha^{-1}) was calculated by Eggers (2002). One study by Karjalainen et al. (2002) calculated values half (6.7 t C ha^{-1}) of those by Karjalainen et al. (2003). Their estimations were for 1990 (or averaged values for 1980 to 1989 in the case of Eggers (2002)) while our estimations are for 2015. The 25 years of difference may explain part of these differences, since production has increased. Another part may be explained by the fact that they used 60 years of pre-simulation with product lifespans of up to 50 years and recycling rates of 33%. Thus, their pre-simulation was probably too short and part of the wood produced at the beginning of the simulation has not yet been totally removed. A strange convergence was found when we compared values reported in different studies for the French wood product sector: Karjalainen et al. (2003) calculated 7.9 t C ha^{-1}, Fortin et al. (2012) determined it to be 8.8 t C ha^{-1} and in this study we arrived at 8.0 t C ha^{-1} based on the FAOSTAT data. Fortin et al. (2012) were not aiming at estimating the carbon stock in French wood products, but only compared different management systems in oak stands. The harvested wood they reported was much larger (1.46 t C ha^{-1} year^{-1}) than the amount we calculated (0.9 t C ha^{-1} year^{-1}), but they allocated a larger proportion of harvested wood to paper products (with low average lifespans) than we did. Actually, the disadvantages of lower graded wood are compensated by the higher production levels. In contrast, the study by Karjalainen et al. (2003) used lower values of harvested wood (0.62 t C ha^{-1} year^{-1}), but allocated large amounts of it to products with medium average lifespans. The uncertainty in the results of our study and the differences found when comparing them with other studies highlight the importance of an accurate representation of round wood allocation and wood product conversion efficiencies in the wood industries.

4.6. Policy relevance

The cascade use of forest biomass has become more policy-relevant in recent years and it is expected to become even more so in the future (Rockström et al., 2017). Therefore, a good representation of cascade chains in wood product models will become more relevant when simulating future scenarios. The use of infinite loops should by all means be replaced with limited number of steps for the cascade chain, especially when recycling rates are high and lifespans are long. The uncertainties in estimating the allocation parameters must be further reduced as well. Shared efforts between governments, the private sector and researchers should be promoted to achieve these goals with geographically specific data to be able to better estimate the climate change mitigation potential of the wood product sector. Especially the private sector should put more effort in disclosing wood product parameters through a shared effort aiming at better benchmarking the environmental quality of their products compared to competitive materials. Shared efforts should also promote the development of new product designs and material technologies to enhance cascading towards the *High quality wood benchmark* scenario (use of wood for long-lived products, high recycling rates and long cascade chains), where much larger amounts of carbon can be stored. Finally, the global warming potential of wood products and their substitutes (Butarbutar et al., 2016; Gustavsson et al., 2006, 2017; Oliver et al., 2014), an aspect not included in this study, should also be considered in future analysis. Similar to an average energy substitution factor in the heating and electricity section (fossil fuel comparator), the European Commission may consider having also an average material substitution factor for replacing fossil fuel intensive materials like steel or concrete by wood.

5. Conclusions

Wood product models estimating recycling of wood products by infinite recycling loops significantly overestimate carbon stock in wood products. To overcome such errors, it is deemed to represent recycling more realistically by applying wood product models containing cascading steps. In addition, the uncertainty of allocation parameters creates an important variation in the results of wood product models. Consequently, more emphasis should be given to reliable data on current allocation processes and its realistic representation in models. Finally, the results also indicated that carbon stock in wood products can be vastly increased by improving cascade chains, mainly for long-lived products, with obvious climate change mitigation effects.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.09.135.

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