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Accounting for Biogenic Carbon and End-of-Life Allocation in Life Cycle Assessment of Multi-Output Wood Cascade Systems

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Abstract

Wood cascade systems composed of products with long service lives can contribute to carbon storage, resource efficiency and circular economy. The environmental assessment of such multi-output systems is however challenging due to (i) multiple products and recycling steps, and (ii) the distribution of emissions, particularly of biogenic CO_2, over long time spans. In Life Cycle Assessment (LCA), the former is usually dealt through end-of-life (EoL) allocation methods, while the latter is assessed via biogenic carbon accounting (BCA) methods. This article aims to assess how different BCA and EoL allocation methods may influence the LCA results of wood cascade systems, particularly their biogenic carbon footprint (BCF), both at supply chain and product levels. Six BCA methods and five EoL allocation methods were analysed, combined and applied to a wood cascade system delivering multiple products: (1) flooring, (4) particleboard (PB) and (5) electricity (reference flow: 1 m^3 wood). At supply chain level (prior to the application of EoL allocation methods), distinct BCFs were obtained ranging from -211 to +52 $kgCO_2eq/m^3$ of wood (as input). At product level, when applying the different EoL allocation methods, the variability further increased. For instance, the BCF of PB ranged from -5.61 to +0.04 $kgCO_2eq/kgPB$; while the BCF of electricity ranged from -0.50 to +0.39 $kgCO_2eq/kWh$ (considering results within the 25-75 percentiles). Other factors influencing the results were the assumptions regarding the timing of forest growth, the stage in the cascade chain, the recycling content and the EoL scenario. A proper understanding of the influence of the BCA and EoL allocation methods and their assumptions on the BCF of wood cascading products is key, especially for countries/regions promoting a circular economy.

Keywords: Environmental impact, recycling, timber products, circular economy

1. Introduction

Both energy and material use of wood can contribute to mitigating climate change when replacing carbon intensive materials. Using wood in products with long service lives can additionally contribute to increasing the amount and time of carbon (C) stored in the anthroposphere. Cascading the use of wood – the multiple material utilizations of wood resources prior to their conversion into energy (Sirkin and Houten, 1994) – has been pointed out as a strategy to improve resource efficiency and contribute to the circular economy by extending the service life of the wood resource (Carus and Dammer, 2018). The environmental assessment of such multi-output cascade systems is challenging due to the multiple products and recycling steps involved, and the distribution of emissions, particularly of biogenic CO_2, over long time spans.

The treatment of biogenic C emissions and sequestration is a controversial issue in life cycle assessment (LCA) and product carbon footprinting (Brandão et al., 2013; Guinée et al., 2009) and the so-called climate neutrality of biomass has been questioned (Helin et al., 2013; Johnson, 2009; Levasseur et al., 2012; Zanchi et al., 2010). Although a sustainably managed forest system is usually considered C neutral, the timing difference between emission and sequestration of biogenic C potentially results in global warming if sequestration lags behind emission (Helin et al., 2013). In woody biomass cascade systems, emissions and sequestration of biogenic CO_2 usually occur at different points in time, but, in most LCA studies the related climate change effect is not taken into account: biogenic CO_2 is either not considered or biogenic CO_2 emissions are assumed to balance out CO_2 uptake during biomass growth.

To circumvent this issue, a number of approaches to account for these temporal effects have emerged, focusing on bioenergy at first (e.g. O'Hare et al., 2009; Kendall et al. 2009; Levasseur et al. 2010; Cherubini et al. 2011), and encompassing bio-based materials later (Guest et al., 2013; Levasseur et al., 2013). The issue of biogenic C accounting has also been raised in several standards, such as ISO 14067:2018 (ISO, 2018), Greenhouse Gas (GHG) Protocol (WRI and WBCSD, 2011), International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), and Publicly Available Specifications (PAS) 2050 (BSI, 2011), which either prescribe a method or leave the approach to the user. While several approaches have been reported in literature (Daystar et al., 2017; De Rosa et al., 2018; Levasseur et al., 2013), there is still a lack of consensus regarding which methodologies for dynamic accounting of C flows to employ in carbon footprinting and LCA studies.

Another relevant issue regarding wood cascade system in LCA is the allocation of burdens and benefits between the multiple products along the cascade. While assigning a "zero burden" to secondary materials should be avoided when performing LCA in circular economy (Djuric Ilic et al. 2018), it is unclear how one should allocate the burdens and benefits of recycling materials throughout their sequence of applications. In that sense, the LCA community has for a long time discussed allocation procedures for recycling (ISO 2006a), which will be called end-of-life (EoL) allocation in this article. Allocation in LCA deals with the distribution of flows related to the burdens and benefits of shared processes amongst various products in the same value chain. In case of EoL allocation, it refers to distributing the inventory flows (burdens and benefits) of resource use/production processes, recycling processes and related avoided virgin production, landfill and incineration, with and without energy recovery, over the various products in the value chain, which typically goes beyond the system boundaries of each product system.

Even though various EoL allocation methods have been proposed and discussed (Finkbeiner et al. 2012, Allacker et al. 2014, Allacker et al. 2017, Gaudreault 2012, Schrijvers et al., 2016a,b), yet there is no agreement on which procedure is preferred. Nevertheless, various LCA standards and descriptive methods/guides have been developed over the past decades, including EoL allocation rules (and the most recent ones have translated the rules in prescriptive equations to improve consistency). Examples are the EN15804+A1:2013 (CEN 2013), used for Environmental Product Declarations (EPDs) of construction products, and the Product Environmental Footprint (PEF) (European Commission 2013).

The objective of this article is to assess how different biogenic C accounting (BCA) methods (and assumptions) and different EoL allocation methods may influence the biogenic carbon footprint (BCF) of wood cascade systems. For that, a multi-output wood cascade system providing wood flooring, particleboard (PB) and bioenergy, at different points in time, from 1 m^3 of wood harvested from the forest, is used as case study. A selection of BCA methods was first applied at supply chain level and was then combined with a selection of EoL allocation methods applied at product level (all methods are described in section 2 and in the supplementary materials (SM)).

2. Material and methods

This section describes the BCA methods and time-related assumptions (section 2.1), the EoL allocation methods and respective assumptions (section 2.2), and the wood cascade case study (section 2.3).

2.1 Biogenic carbon accounting (BCA) methods and assumptions

Six BCA methods based on the Global Warming Potential (GWP) were selected for the analysis: (i) Fixed GWP, which assigns the same characterization factor irrespective of the time at which the uptake/emission occurs; (ii) Zero-GWP, which assigns a characterization factor of 0 to any biogenic CO_2 flow; two simplified methods used in carbon footprint standards – (iii) ILCD (European Commission, 2010) and (iv) PAS 2050 (BSI, 2011) – that assign a credit for each year of C storage in the anthroposphere; (v) biogenic global warming potential (GWP_{bio}) factors (Guest et al., 2013) that integrate the effect of timing of C sequestration in both terrestrial and anthroposphere sinks; and (vi) DynLCA (Levasseur et al., 2010) that accounts for the effect of timing of CO_2 flows using an accounting-based method considering both emissions and sequestrations over time. Additionally, different time-related assumptions were analysed, namely the time window of the Global Warming (GW) assessment (fixed or variable), the timing of CO_2 uptake in the forest (past growth, regrowth, no accounting) and in the anthroposphere, and the setting of the initial temporal boundary (at plantation or at harvest) and corresponding timeframe of GW effects. In total, seven combinations of assumptions and BCA methods were assessed, as summarized in Table 1. A detailed description of the BCA methods is presented in SM (Section 1).

Table 1 Biogenic carbon accounting (BCA) methods and time-related assumptions.

Time-related assumptions		**BCA methods**						
		Fixed GWP & Zero-GWP	**ILCD**	**PAS 2050**	**GWP$_{bio}$**	**DynLCA**		
						Past growth (p)	**Regrowth (r)**	**No accounting (n)**
Temporal boundary	**Timeframe of wood (re)growth**	[a]	n.a.	n.a.	50	50	50	n.a.
	Timeframe of wood utilization	[a]	Variable (0-55 years)	Variable (0-55 years)	Variable (0-55 years)	Variable (0-55 years)	Variable (0-55 years)	Variable (0-55 years)
	Timeframe of GW effects	100 years	100 years	100 years	100 years	150 years	100 years	100 years
	Time window of GW effects	Fixed	Fixed	Fixed	Variable	Variable	Variable	Variable
	Initial temporal boundary	[a]	At the time forest is harvested (t=0)	At the time forest is harvested (t=0)	At the time forest is harvested (t=0)	At the time forest is planted (t=-50)	At the time forest is harvested (t=0)	At the time forest is harvested (t=0)
	Endpoint in time	[a]	100 years after harvest	100 years after harvest	100 years after harvest	100 years after harvest/150 years after plantation	100 years after harvest	100 years after harvest
Temporal effect of C storage	**In forest**	[a]	Not considered	Not considered	Forest regrowth after harvest	Forest growth before harvest (past growth)	Forest regrowth after harvest	Not considered
	In the anthroposphere	[a]	Considered	Considered	Considered	Considered	Considered	Considered

[a] No temporal information is considered – emissions and uptakes are assumed to occur at the same time.

n.a. not applicable.

Both GWP_{bio} and DynLCA consider a variable time horizon (TH) as opposed to the fixed TH of the other approaches. This means that the GW effect of CO_2 emissions is considered over the period between the emission and the fixed endpoint in time set for the assessment, whilst for the remaining approaches, the GW effect of the CO_2 emission is assessed over a fixed period, irrespective of the time at which the emission occurs. The endpoint in time was set to 100 years following harvest for all cases. Regarding the temporal effect of C storage, GWP_{bio} considers the time of C storage in the forest (for 50 years), whilst PAS 2050 and ILCD do not. The DynLCA method allows the user to consider the time of C storage in the forest or not. The temporal effect of C storage in bio-based products is considered by all methods, except the Fixed GWP and the Zero-GWP. For the latter, no temporal information is considered; both CO_2 emission and uptake are assumed to occur at the same time.

The setting of the initial temporal boundary is also a critical aspect as the GW impact is very sensitive to the dynamics of the carbon sequestration and to its timing (Levasseur et al., 2013). In ILCD, PAS 2050 and GWP_{bio} approaches, the temporal boundary starts at the moment the trees are harvested for wood (t=0). The latter also considers the regrowth of the forest in the calculation of the GWP_{bio} factors. For the DynLCA method, three options are allowed (see Table 1): DynLCA-p, which considers past growth, setting the initial temporal boundary at t=-r; DynLCA-r, which considers regrowth, and DynLCA-n, which does not account for forest growth, setting the initial temporal boundary at t=0. Additional details about time-related assumptions can be found in SM (Section 1).

2.2 End-of-life (EoL) allocation methods and assumptions

In order to investigate the influence of the choice of EoL allocation method on the BCF of different products in a wood cascade system, five EoL allocation methods (A to E, below) were selected. Four of the five EoL allocation approaches are chosen from current European standards and guidelines, broadly used for environmental labelling. The fifth approach takes into account the number of subsequent uses of the recycled material as recommended by ISO (2006b) and was translated into an equation by Allacker et al. (2017).

A. EC PEF original EoL approach, using 50/50 allocation (European Commission 2013);
B. EC PEF circular footprint formula from PEF Guidance v. 6.3, using 80/20 allocation in case of wood products (European Commission 2018);
C. CEN TC 350: standard EN 15804+A1:2013, using 100/0 allocation (CEN 2013);
D. CEN TC 350: draft of the second amendment to EN 15804+A1:2013 (EN 15804+A1:2013+A2:2017), using net output flow approach, i.e., 0/100 allocation (unpublished work);

E. Allocation approach taking into account the number of recycling loops (Allacker et al., 2017).

The concept and formulas of the five EoL allocation methods are described in SM (Section 2). An in-depth discussion on and general comparison of these various EoL allocation methods is out of scope of this paper, but can be found in Allacker et al. (2014, 2017) and Schrijvers (2016a). The current paper focuses on the consequences of applying these different EoL allocation approaches to a wood cascading system. As can be seen from the formulas, for most approaches, a different EoL allocation is used for recycling and incineration processes. The reason is that energy recovery from incineration processes is not considered a product, but a process. A difference is moreover noticed between products being incinerated with energy recovery or landfilled, while incineration could also be seen as a disposal process. These differences in allocation might have an important influence on the comparative results of the products in a cascade system; therefore, two sensitivity analyses were performed to the baseline (i.e. the scenario that follows the EoL formulas as they have been developed):

- Baseline: EoL formulas applied as they are developed (see equations 1 to 11 in SM) and assuming incineration at the end of the service life of products occurs before the end of waste state is reached;
- Sensitivity 1: electricity is assumed as a product, and hence the EoL allocation for incineration processes is the same as for recycling processes;
- Sensitivity 2: incineration processes are assumed as disposal processes.

Avoided biogenic carbon emissions due to energy recovery are not considered.

2.3 Case study

A hypothetical case study was designed to simulate a typical multi-output wood cascade system, which produces wood flooring, PB and bioenergy, depicted in Figure 1. The reference flow is 1 m^3 of wood harvested from a forest. Wood is assumed to be provided by a single-stand plantation of Scots pine (*Pinus sylvestris*) with a rotation period of 50 years. The wood density is assumed 470 kg (dry) m^{-3} and the carbon content 50% (dry mass). Three different co-occurring supply chains were considered:

- *Supply chain A (SC-A)*: uses timber wood for *flooring A1*, which is at the EoL recycled into PB (*recycled PB A2*), which is subsequently (partly) recycled into another PB (*recycled PB A3*) and (partly) incinerated for energy generation (*Electricity recycled PB A2*); the second PB is also incinerated at the EoL for electricity generation (*Electricity recycled PB A3*);
- *Supply chain B (SC-B)*: uses part of the wood residues, both from forest and industry (sawmill), for PB production (*virgin PB B1*), which is (partly) recycled at the EoL into another PB (*recycled PB B2*) and (partly) incinerated for energy generation (*Electricity EoL virgin*

PB B1); the second PB is also incinerated at the EoL for energy generation (*Electricity recycled PB B2*);

– *Supply chain C (SC-C)*: uses the remaining part of the wood residues (from forest and industry) for electricity generation (*"virgin" bioenergy*).

The analysis focuses on the (wood) material and traces biogenic C flows along the three supply chains. Only biogenic C flows are considered, that is CO_2 uptake by trees, biogenic C stored in wood/wood products, and emissions of biogenic CO_2. Any additional C (or greenhouse gas) flows (e.g. from transportation of wood/wood products, manufacturing of auxiliary materials) and any amount of (virgin) wood necessary to produce PBs other than that coming from the reference flow (1 m^3 of wood harvested from forest) are not accounted for. The C embedded in the wood is assumed to be eventually released as CO_2 at some point in the supply chains (at the final stage of the cascade system, biomass is used for electricity generation, assuming complete combustion). The inventory of biogenic CO_2 flows along the three supply chains, including their timing, is depicted in Fig. 1. The timing of the uptake of CO_2 in the forest depends on the assumption regarding the initial temporal boundary, as detailed in SM (Section 1.2). Additional modelling parameters and assumptions are described in SM (Section 3).

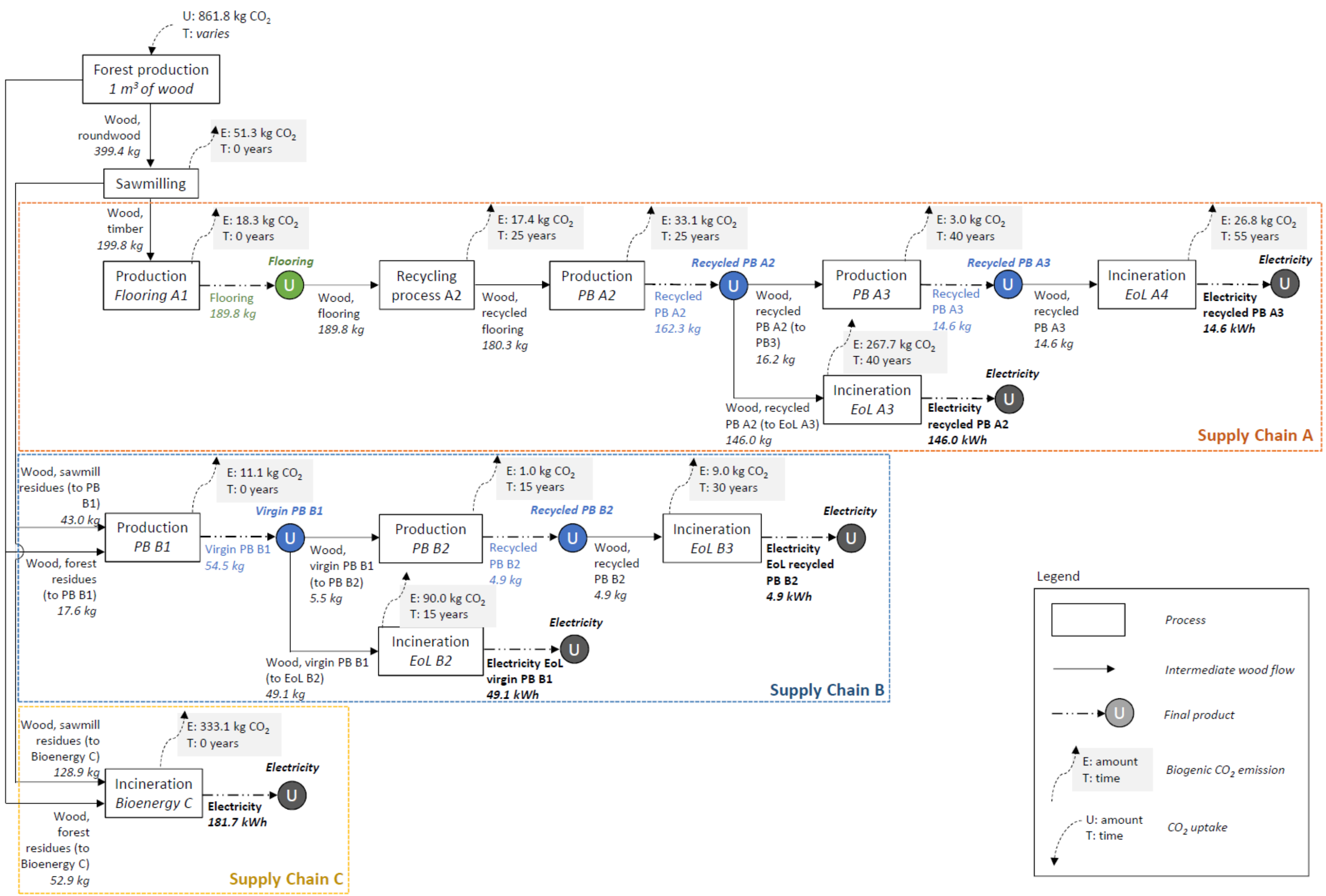

Fig. 1 System under study (reference flow: 1 m^3 of wood). Year 0 is defined at the moment of harvest. The timing of CO_2 uptake varies (see SM section 1.2): -50 to 0 (DynLCA-p); 0 to 50 (GWP_{bio} and DynLCA-r); 0 (ILCD, PAS 2050, DynLCA-n). Carbon content of wood is 50% (dry mass). PB: particleboard; EoL: end-of-life; A1: 1st life cycle in supply chain A; A2: 2nd life cycle in supply chain A; A3: 3rd life cycle in supply chain A; B1: 1st life cycle in supply chain B; B2: 2nd life cycle in supply chain B. Modelling parameters and assumptions are described in SM (Section 3).

3. Results

In this section the results are presented in three levels. In section 3.1, the calculated characterization factors for the biogenic CO_2 emissions are presented based on the different BCA methods. Section 3.2 presents the GW impact of biogenic CO_2 emissions of the overall wood cascade system and the three subsystems/supply chains. Section 3.3 shows the BCF variability (for the specific products) due to EoL allocation and BCA methods. Detailed results for the DynLCA method, the time-dependent allocated flows, and the BCF variability due to each specific BCA method are presented in SM, in sections 4, 5 and 6, respectively.

3.1 Characterization factors for biogenic CO_2 emissions

Table 2 presents the GW characterization factors (CFs) for biogenic CO_2 emissions for the eight combinations of BCA methods and assumptions as a function of the time at which the emission occurs (*t*). For the GWP_{bio}, CFs were taken from Guest et al. (2013a), except for *t*=15, *t*=25, and *t*=55, which are linear interpolations of the values in Guest et al. (2013a). For DynLCA-n, DynLCA-r, and DynLCA-p, CFs were calculated based on the DynLCA method (Levasseur et al., 2010) by simulating a generic case considering the uptake of 1 kg of CO_2 distributed over a full rotation, either before (DynLCA-p) or after (DynLCA-r) the emission, or as a pulse (DynLCA-n), and the pulse emission of 1 kg of CO_2 at time *t*.

The characterization factors in Table 2 represent how much a pulse emission of biogenic CO_2 at time *t* contributes to GW in the time horizon considered as compared to a pulse (fossil) CO_2 emission at *t*=0. A negative characterization factor indicates that, per emission of biogenic CO_2 at time *t*, there was a previous uptake of CO_2 by the trees that (partly) compensated the radiative forcing caused by that emission, resulting in a net negative radiative forcing in the time horizon of the assessment.

Table 2 Characterization factors for the assessment of GW impacts of biogenic CO_2 emissions for the different BCA methods and assumptions as a function of the time (*t*) at which the emission occurs.

t (year)	**Characterization factors** ($kgCO_2eq/kgbiogenicCO_2$)							
	Zero-GWP	**Fixed GWP**	**ILCD**	**PAS 2050**	**GWG_{bio}**[a]	**DynLCA-p**	**DynLCA-r**[a]	**DynLCA-n**
0	0	1	0	0	0.20	-0.14	0.20	0
15	0	1	-0.15	-0.11	0.09	-0.23	0.08	-0.12
25	0	1	-0.25	-0.19	0.02	-0.29	0.00	-0.20
30	0	1	-0.30	-0.30	-0.03	-0.32	-0.04	-0.24
40	0	1	-0.40	-0.40	-0.12	-0.38	-0.13	-0.33
55	0	1	-0.55	-0.55	-0.26	-0.48	-0.27	-0.47

[a] Characterization factors for GWPbio and DynLCA-r should be equivalent; however, they differ here due to rounding and truncations.

3.2 Global warming impact of biogenic CO_2 emissions of the wood cascade (sub)system(s)

Figure 2 shows the GW impact of biogenic CO_2 emissions (for a reference flow of 1 m^3 of wood) for the overall wood cascade system and for the three separate subsystems/supply chains (SC-A to C) for all BCA methods and time-related assumptions analysed. The carbon content of the wood (and therefore CO_2 uptake) is allocated between the various subsystems according to mass. Results show that different BCA methods and time-related assumptions can lead to opposite GW impacts of biogenic CO_2 along the supply chains – either resulting in a net negative (e.g. ILCD, PAS 2050) or positive (e.g. GWP_{bio}) contribution to climate change. For long cascade systems, such as SC-A, a negative impact is obtained with all BCA methods and assumptions, but the difference may reach 79%. For shorter cascade systems (SC-B) or for bioenergy chains (SC-C), either a negative or a positive effect on GW is calculated.

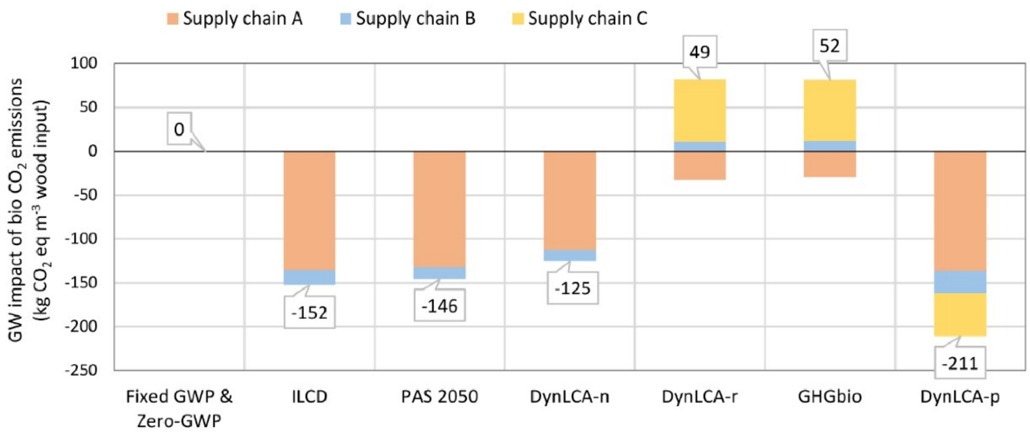

Fig. 2 Global warming impact of biogenic CO_2 emissions at supply chain level for all combinations of BCA methods and time-related assumptions.

Table 3 presents the GW impact of biogenic CO_2 emissions for all supply chains normalized per kg of biogenic CO_2. Four main groups of methods with similar results are distinguished, which in turn encompass similar time-related assumptions: I – Fixed GWP and Zero-GWP; II – ILCD, PAS2050 and DynLCA-n; III – GWP_{bio} and DynLCA-r; and IV - DynLCA-p. In Group I, all uptakes and emissions either balance out (Fixed GWP) and the timing of emissions is not considered or biogenic CO_2 flows are not accounted for (Zero-GWP) leading either way to a null GW impact of biogenic CO_2 emissions in every chain. In Group II, benefits are calculated for chains with materials (SC-A and SC-B), due to the credit introduced for biogenic C storage within products. On the other hand, the impact of the energy chain (SC-C) is null. Overall, different forest growth periods are not taken into account. In Group III, benefits are calculated depending on the temporal balance between (a) wood growth and (b) storage time in the product. In SC-A, impact is negative because the storage time is long (up to 55 years); whilst in both SC-B and SC-

C, the impact is positive because wood takes a long time to grow (50 years) and products have a relatively short service life (SC-B: up to 35 years; SC-C: wood is incinerated for energy in year 0). In Group IV, GW impacts are always beneficial because it considers the CO_2 uptake by trees occurring before the emission – wood is assumed to be grown specifically to be used as raw material for these products, so the benefit as wood sequesters C during growth (in forest) is allocated to these products.

Table 3 Global warming impact per kg biogenic CO_2 for the overall system and the three subsystems/supply chains depending on the group (I-IV) of BCA methods.

	Accounting for the time of CO_2 uptake in biomass growth	**Accounting for the time of CO_2 storage in products**	**GW impact of biogenic CO_2 emissions** (kg CO_2 eq/kg bioCO_2)			
			Whole system	**SC-A**	**SC-B**	**SC-C**
I	No	No	0	0	0	0
II	No	Yes	-0.18 to -0.15	-0.34 to -0.29	-0.14 to -0.11	0
III	Yes (regrowth)	Yes	0.06	-0.07	0.09 to 0.10	0.20
IV	Yes (past growth)	Yes	-0.24	-0.35	-0.22	-0.14

I: Fixed GWP and Zero-GWP; II: ILCD, PAS2050 and DynLCA-n; III: GWP_{bio} and DynLCA-r; IV: DynLCA-p.

Figures S2-S4 in SM (section 4) show the effect over time for the three assumptions regarding forest uptake (past growth, regrowth and no accounting) as calculated by the DynLCA method. Whilst the effect of CO_2 emissions is the same in all cases (same emission profile), the effect of the CO_2 uptake on the GW impact depends on its timing relatively to the endpoint in time. Uptakes of CO_2 from the atmosphere in the beginning of the assessment period and before harvest have a higher effect on GW than the emissions after harvest because the time horizon over which the effect of these uptakes is accounted for is longer.

Overall, the differences between BCA methods with similar time-related assumptions, i.e. within the Group I-IV (up to 20%), are lower than the differences between BCA methods considering different time-related assumptions, i.e. between each Group I-IV (above 100%). This leads to the conclusion that assumptions about the temporal boundary have higher influence on the results than the BCA method used.

Irrespective of the BCA method and the time-related assumptions considered (except the Fixed GWP), biogenic CO_2 emissions in the supply chain without cascading (SC-C) have higher impacts (or lower benefits) than in any of the cascade systems (SC-A and SC-B). Furthermore, the longer the cascade system the higher the benefits (or lower the impacts) of biogenic CO_2 emissions (SC-A versus SC-B). It should be noted that this rationale applies to biogenic CO_2 emissions only. The overall benefits or impacts of each chain depend on other processes and GHG flows that were not assessed here.

3.3 Biogenic carbon footprint (BCF) variability at product level due to EoL allocation and BCA methods

The five EoL allocation methods were applied to the various products in the three supply chains to investigate how the allocated flows differ among the different EoL allocation methods and the different approaches to incineration (i.e. baseline approach, sensitivity 1 and sensitivity 2). The allocated flows are presented in SM (section 5). Furthermore, these allocated flows were assessed with the eight BCA methods (using the CFs from Table 2). Results for two types of products in the wood cascade case, i.e. the (fractions of) PB and electricity are presented in sections 3.3.1 and 3.3.2. respectively. In SM (section 6), all EoL allocation methods and approaches are illustrated for one BCA method, i.e. the GWP_{bio} method (Guest et al. 2013).

It is important to highlight that a direct comparison of the BCF results in section 3.3.1 is not meaningful because it only relates to fractions of PBs (i.e. part of the 1 m^3 of wood harvested used for PB production). Therefore, in section 3.3.3 a "complete" PB is compiled based on various wood fractions (i.e. virgin wood, recycled wood from flooring and recycled wood from PB), which reflects a typical PB in the EU market.

3.3.1 (fractions of) Particleboard (PB)

For the four (fractions of) PBs in the wood cascade case (see Figure 1), five EoL allocation methods have been implemented, with three different scenarios (i.e. baseline, sensitivity 1 and sensitivity 2), generating 15 different allocated flows, as presented in Table S2 (SM). In the next step, eight BCA methods have been implemented. We excluded the values of sensitivity 1 and 2 for the Fixed-GWP method from the analysis, because its implementation was not consistent. Therefore, in total, there were 110 (7*5*3 + 1*5) BCF results, which are presented in a box-plot graph (Figure 3).

The median values of the PB (-0.08, -0.12, -0.21 and -0.51 $kgCO_2eq/kgPB$ for B1, B2, A2 and A3, respectively) decrease the further up they are in the cascade chain. Meanwhile, the range of results, either between the 0.25 and 0.75 percentiles or between the minimum and maximum values, increase the further up they are in the cascade chain. A combination of factors led to this observation, including the higher variability of CF amongst the BCA methods for the emissions occurring later (e.g. at year 55), which are mostly allocated to the products further up in the cascade.

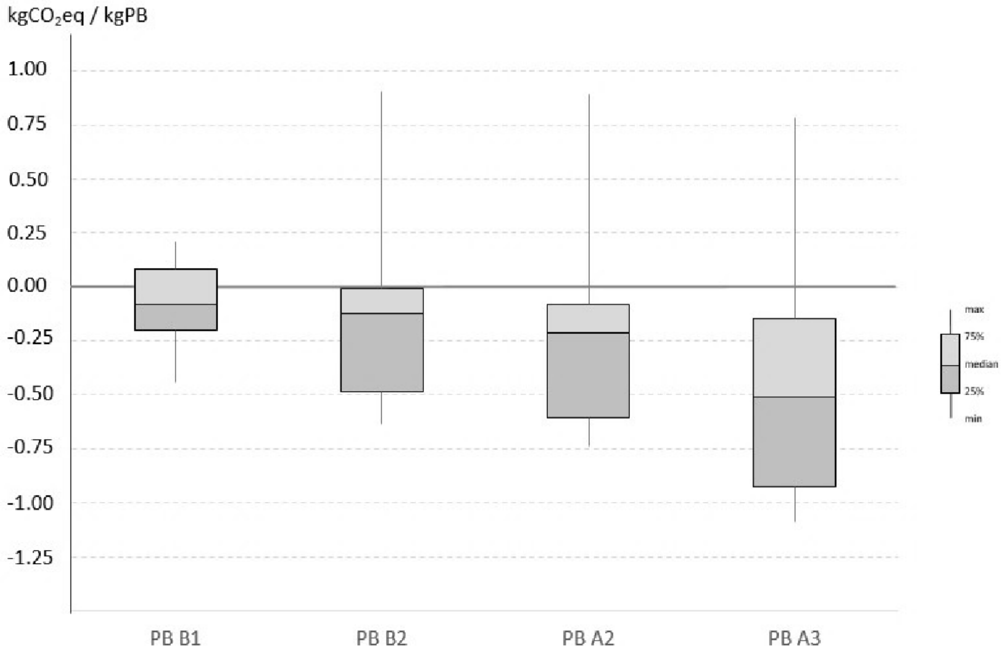

Fig. 3 Variability of different biogenic carbon footprint (BCF) results for (fractions of) PB, based on 110 results

3.3.2 Electricity

For the calculation of the BCF of electricity only the 'Sensitivity 1' is taken into account as it considers the electricity produced at EoL as a co-product and, therefore, emissions were allocated to it as well (see Table S2 in SM). The five different allocated flows were implemented in seven different BCA methods, generating 35 results (Figure 4).

Similar to PBs, the median values (0.00, 0.00, -0.06, -0.22 and -0.43 $kgCO_2eq/kWh$ for C, B1, B2, A2 and A3, respectively) for electricity decrease the further up it is in the cascade chain. For supply chain C, 75% of the results for electricity generation (from virgin biomass) are positive or null, leading to an environmental burden associated with biogenic CO_2 emissions in most cases. On the other hand, at least 75% of the results for electricity generated at PB EoL in both supply chains A and B are negative or null, leading to an environmental benefit associated with biogenic CO_2 emissions (with different degrees). These results are in line with the concept of circular economy, i.e. producing wood for bioenergy carries an environmental burden associated with biogenic CO_2 emissions, while producing wood for multiple purposes (e.g. supply chain A) may have environmental benefits (i.e. when looking solely to the biogenic carbon emissions).

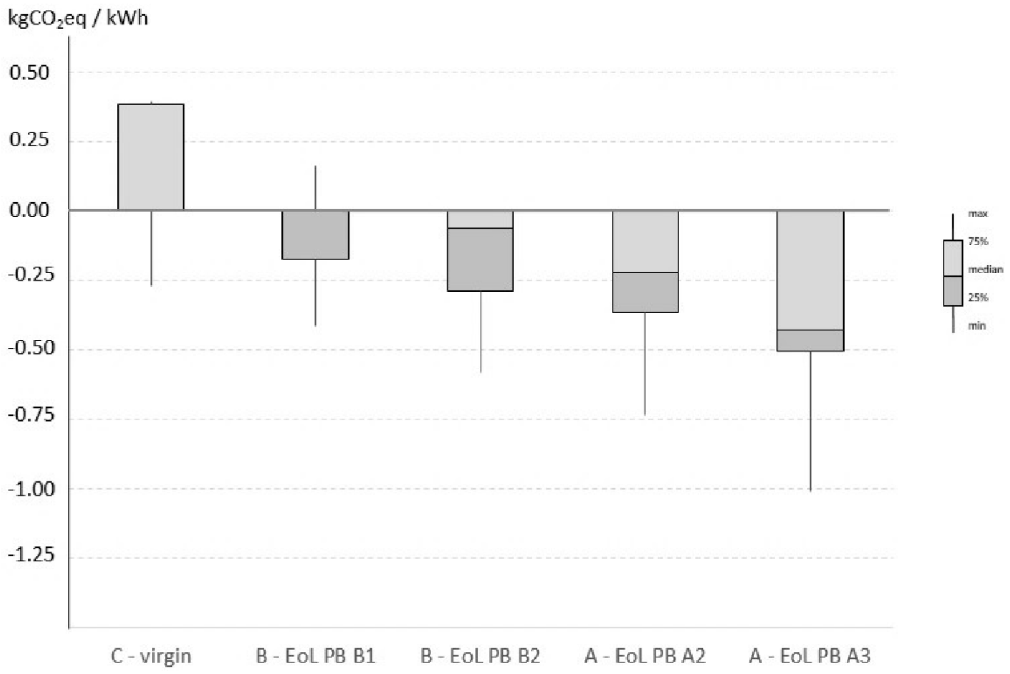

Fig. 4 Variability of different biogenic carbon footprint (BCF) results for electricity, based on 35 results

3.3.3 Comparison amongst (complete) PBs with different recycled content and EoL scenarios

The results in this section are for a "complete" PB, based on various wood fractions (i.e. virgin wood, recycled wood from flooring and recycled wood from PB), representing a typical PB found in the European market. For this analysis, one EoL allocation approach (EC PEF original EoL approach, using 50/50 allocation - baseline) and two BCA methods (GWP_{bio} and PAS2050) were selected. Moreover, two additional aspects were compared within this analysis, i.e. (1) differing the recycled content of the PB (25% virgin and 75% postconsumer wood; or 75% virgin and 25% postconsumer wood); and (2) differing the EoL treatment of the PB (recycling or incineration). This leads to the comparative assessment of eight scenarios.

Table 4 shows that for the scenarios with recycling as EoL treatment, biogenic carbon emissions are very low, yet a BCF ranging between 0.04 and -0.07 kg CO_2eq/kgPB, depending on the recycled content and the BCA method, was obtained. This is mainly because the EoL allocation methods mostly allocated the emissions from the main product (the wood feedstock) at the respective EoL. Therefore, the majority of biogenic carbon emissions were allocated to the product downstream ('n+1' wood cascade) of those products ('n' wood cascade). Consequently, the negative values of BCF are higher for the incineration at EoL scenarios, ranging from -0.33 to -5.61 kgCO_2eq, depending on the recycled content and the BCA method. At least for closed-loop recycling, incineration at EoL is the most probable route for PB, due to technical limitations. Currently, industry can only use up to approximately 10% of its postconsumer wood from PB, due to technical constraints (based on expert knowledge).

Table 4 Biogenic carbon footprint (BCF) of two types of complete PBs with a different recycled content, based on one EoL allocation approach (EC PEF original EoL approach, using 50/50 allocation - baseline scenario), two different BCA methods (GWP_{Bio} and PAS2050) and two different EoL treatments ($kgCO_2eq/kgPB$).

Products	Scenarios	Incineration at EoL		Recycling at EoL	
	Methods	GWP_{bio}	PAS2050	GWP_{bio}	PAS2050
PB with 75% recycled content		-1.45	-5.61	0.02	-0.07
PB with 25% recycled content		-0.33	-2.01	0.04	-0.02

Moreover, the benefits of biogenic carbon emissions are higher in PAS2050 mainly due to its simplified accounting method, which considers only the benefits of storage, and not the burdens associated with the time of forest regrowth (which are considered in GWP_{bio}). Finally, results show that accounting for biogenic CO_2 emissions emphasizes the GW benefit of products with higher recycled content. A 25% recycled content PB would have a BCF between 0.04 and -2.01 $kgCO_2eq/kgPB$, whilst the BCF of a 75% recycled content PB would be between 0.02 and -5.61 $kgCO_2eq/kgPB$, depending on the EoL treatment and the BCA method.

The results should be interpreted with care because this analysis focused on only one EoL allocation method and two BCA methods (GWP_{bio} and PAS2050). Different results are to be expected if other methods are used (as shown in section 3.2), on top of the differences in recycled content and EoL treatment (recycling or incineration).

The relative contribution of the BCF to the overall carbon footprint of PB can be inferred by comparing it to the (traditionally accounted) fossil carbon footprint of PB. For instance, Garcia and Freire (2014) reported values between +0.25 and +0.40 of $kgCO_2eq/kgPB$ for fossil carbon footprint, depending on the method/approach (and system boundaries). Ecoinvent's European PB (ecoinvent, 2018) has a fossil carbon footprint of approximately +0.45 $kgCO_2eq/kgPB$. However, the latter value cannot be summed up with our values of Table 4 in a straightforward way due to ecoinvent's different EoL allocation method (100/0) and different PB's recycled content (30%). Nevertheless, it can be concluded that the BCF of PB can be in the same order of magnitude as the fossil carbon footprint.

4. Discussion

This section discusses the advantages and limitations of the available BCA methods (4.1), the effects of accounting for time perspective (4.2), and an outlook for EoL allocation methods (4.3).

4.1 Practical advantages and limitations of the BCA methods

As noted in Section 3.2, the choice of BCA method is constrained by (i) the assumptions regarding the timing of forest growth and (ii) the level of detail required to model the forest system. If regrowth is the chosen approach, then both GWP_{bio} and DynLCA can be used to assess impacts of biogenic CO_2 emissions, with theoretically equivalent results (Breton et al., 2018); the latter being preferable if the assessment of other forest carbon pools (than aboveground biomass) and different time horizons is required. In case of no accounting for the time it takes to (re)grow the biomass (Group II), both ILCD and PAS 2050 simplified methods lead to very similar results (3% difference), but using the DynLCA increases the impacts by roughly 20%. The difference in results between these methods is lower as the storage time in products increases (e.g. chain A versus chain B). The advantage of both ILCD and DynLCA over PAS 2050 is that those methods can capture the effect of GHG emissions other than biogenic CO_2 and are, therefore, preferable when assessing complete life cycle GW impacts. The DynLCA results are more accurate than the ILCD results, but computational time and effort are also higher. Furthermore, both PAS2050 and ILCD are only applicable to a time horizon of 100 years.

As ILCD, PAS2050 and GWP_{bio} can be directly applied to biogenic CO_2 flows, these methods are more practical to use within the standard LCA framework, especially when assessing complex product systems. However, the DynLCA is the only method that provides a straightforward way of calculating impacts irrespective of the assumptions made and the level of detail required to model the forest system. It is also the only method that can be used to assess biogenic CO_2 impacts considering the growth of trees before harvest. The model is flexible regarding time horizon, rotation period, growth model, and biomass pools considered, and can be applied to all GHG (other than biogenic CO_2). Therefore, if different assumptions need to be tested, the DynLCA would be the preferable choice. It should be stressed that the GWP_{bio} approach can be used to calculate CFs considering other time horizons, growth models and biomass pools (Cherubini et al., 2011), but calculation time and effort is higher than the DynLCA, which already provides a calculation tool, and only the regrowth perspective and biogenic C emissions can be analysed.

4.2 Time-related assumptions of different groups (I-IV) of BCA methods

Results are highly sensitive to the assumption about the initial temporal boundary, as GW impacts of biogenic CO_2 emissions can be positive, negative or null depending on whether regrowth, past growth or no accounting of forest growth is chosen. The BCA methods in Group I and II ignore the time it takes for the forest to grow, assuming that a carbon neutral forest system is climate neutral. This simplification puts emphasis on the short-term climate benefits of the temporal storage of C in wood products, thus favouring any duration of storage in the anthroposphere and, consequently, leading to net negative contributions of biogenic CO_2 emissions to GW. However, climate neutrality may only be accomplished in the long term, particularly for long-rotation species; therefore, these methods may underestimate the long-term GW impacts of these systems.

In Group IV methods, which consider past growth, the starting point of the assessment is moved backwards in time to when the forest was planted. The rationale for this approach is that trees previously sequestered C, and, therefore, burning wood now or in the future would simply return CO_2 that was previously absorbed by the trees to the atmosphere (Helin et al., 2013; Ter-Mikaelian et al., 2015). Biogenic CO_2 emissions from any use of the wood, including for bioenergy, would lead to a net negative contribution to GW, because the past storage of C in the forest is accounted for, contributing to mitigate climate change. Likewise, harvesting a long-rotation forest would be favoured over a short-rotation one. Conversely, Group III methods consider regrowth after harvest (i.e. the starting point of the assessment is the moment of harvest of a fully-grown forest), assuming a forward-looking perspective. The rationale is that an emission of (biogenic) CO_2 to the atmosphere now will have an impact on climate change that is measured taking into account the current concentration of CO_2 – that effect is only mitigated if a new stand is planted, reabsorbing the released CO_2. In this approach, biogenic CO_2 emissions can lead to a net negative, positive or null contribution to climate change depending on the rotation period and the storage time in the anthroposphere. The longer the rotation period of the trees' species, the longer the storage time in the anthroposphere needs to be to offset the GW contribution of biogenic C emissions. As a corollary, biogenic CO_2 emissions of bioenergy from long rotation species, for instance, generally have a higher climate change effect than those from short rotation ones (Cherubini et al., 2011) – this effect is not captured in any of the other groups of methods assessed. When considering these aspects, the extension of the service life of biomass materials through cascading (potentially having a negative impact on GW) is favoured over using virgin biomass for energy (potentially having a positive impact on GW).

Accounting for the time effect of biogenic CO_2 emissions is important when the goal is CO_2 emission reduction in the short term and when the service life of wood materials can be extended, such as through wood cascading. Furthermore, it should consider the time it takes to regrow the trees, that is, to sequester an amount of C equivalent to that released in the cascade system. To this end, Group III methods are the most suited. However, if a land use change has occurred (e.g. afforestation, deforestation), the loss or uptake of C due to the conversion of land from previous use to current forest use needs to be considered.

4.3 Alternative EoL allocation methods

Regarding EoL allocation methods, five operational methods were selected for analysis. Other alternative approaches for EoL allocation also exist, but not in an operational way (e.g. equations). For instance, a 50/50 approach could be implemented via another approach (Gaudreault 2012), or as described in the partitioning approach in Schrijvers et al (2016b). In Gaudreault (2012), the 50/50 method allocates 50% of the environmental load of virgin material production and final waste management to the product using the virgin material, and the remaining 50% to any products not further recycled. In Schrijvers et al (2016b), the partitioning approach suggests a 50-25-25% distribution of the burdens of primary production for a three-product cascade. If these other approaches were implemented, the results of Table 4 would be different. For instance, in case an alternative approach of EoL allocation method would have distributed the carbon storage benefits along the value chain, instead of focusing on the point of the biogenic CO_2 emission (at the incineration), the PB with incineration at EoL would not have significantly better results than the PB with recycling at EoL (Table 4). However, some of these approaches (that may sound more fair) often require knowledge about all the subsequent life cycles, making the operationalization of EoL allocation methods more difficult, which (on the other hand) can be interpreted as a future challenge for the LCA community.

5. Conclusions

In this paper, several BCA methods (with different time-related assumptions) were applied to assess the climate change impact of biogenic CO_2 emissions from a multi-output wood cascade system in a life cycle perspective. Furthermore, the application of these methods was combined with different EoL allocation methods, in order to assign benefits and burdens amongst the various products in the wood cascade chain for the assessment of the BCF of these products (focused, though, on the wood-content of these products).

When applying different BCA methods (prior to EoL allocation), results were found to be highly sensitive to how the timing of CO_2 uptake in the forest is accounted for, rather than the BCA method used. In fact, before choosing the BCA method, it is necessary to set how forest modelling (e.g. temporal boundary, biomass pools, and rotation period) will be tackled, according to the goal and scope of the LCA study, because the different methods entail different perspectives to this issue.

Methods that disregard the time of forest growth, as in the Fixed GWP, PAS 2050, ILCD, and DynLCA-n, assume that a carbon neutral forest system is climate neutral. However, this simplification is only valid for short rotation forests, whilst for long rotation ones, such as the one assessed, climate neutrality is only accomplished with long term carbon storage (in products). From a sustainability perspective, accounting for the future timing effect of biogenic CO_2 flows is important when the goal is climate change mitigation in the short term. In this perspective, the regrowth assumption, as employed in Group III methods (GWP_{bio} and DynLCA-r), may be more meaningful in most cases. However, for the specific cases in which wood is a product of afforestation, starting the assessment at the moment the forest is planted is suggested.

GW results for longer cascades are less sensitive to the different methods and assumptions. Nevertheless, differences are still noteworthy and potentially impactful on the conclusions regarding climate effects of cascade systems. Therefore, different assumptions should be tested. The only method analysed that is flexible enough to accommodate the analysis of different assumptions and that is able to provide an overall perspective of the climate implications of wood-based systems is the DynLCA, even if calculation effort and time make it not practical for the assessment of large systems. If following the regrowth approach and assessing biogenic CO_2 emissions only, GWP_{bio} CFs are easier to apply, whilst providing similar results to DynLCA.

As regards the climate change effect of biogenic CO_2, longer cascade chains provide higher benefits than shorter ones. The assessment focused exclusively on biogenic CO_2 emissions. Including other climate change forcers (e.g. other GHGs, changes in albedo) is important to get a comprehensive assessment of the climate change effect of the multi-output cascade system analysed. In fact, other GHG emissions may offset the benefits of delaying biogenic CO_2 emissions through biomass cascading. The assessment should also consider the displaced non-renewable alternatives for a full understanding of the climate change effects of biomass cascading in the short term. The controversy about the effect of different spatial boundaries was also not explored here.

Furthermore, when a product level assessment is entailed, as in typical attributional LCA and carbon footprint studies, different EoL allocation methods may be used. Five EoL allocation methods were used to allocate the flows of biogenic CO_2 (related to the wood part) of the different products in the wood cascade system. The comparison clearly shows that the allocated flows of biogenic CO_2 to the various products differs according to the method used. In consequence, the moment in time this flow of CO_2 is 'occurring' varies with the EoL method chosen (see Table S2). As the moment of occurrence of an emission has an influence on the CF in some of the BCA methods, this means that the various combinations of EoL allocation and BCA methods will not only lead to a different climate change impact of the various products, but also to a different climate change impact of the whole wood cascade system.

When depending on both the EoL allocation method and the BCA method, there is a high variability of results for the (biogenic) carbon footprint of products from wood cascading. Biogenic carbon flows can be depicted as bringing an additional burden to climate change (e.g. as in 75% of the combinations for bioenergy from virgin wood – supply chain C), or as an environmental benefit to climate change in the time horizon considered (e.g. -1.45 $kgCO_2eq/kgPB$, for a PB with 75% recycled content and incineration at EoL). Moreover, the BCF was often in the same order of magnitude as the fossil carbon footprint, which highlights the relevance of accounting for the former. Other factors were also relevant in the variability of the BCF results at product level, such as the recycling content and the EoL scenario considered.

A proper understanding of the influence of the BCA method and the EoL allocation method on the LCA and carbon footprint of wood cascading products is key to decision-making, especially for countries/regions promoting a circular economy (as Europe). To be able to make these methods more operational, BCA methods could develop characterization factors (or provide guidance on implementation) for non-homogenous biobased products as well, as it is the case of PB and other wood-based products (e.g. fiberboard). Moreover, EoL allocation methods should properly allocate the biogenic carbon emissions (at EoL) throughout the products in the wood cascade to be in line with BCA methods and the concept of circular economy. Alternatively, accounting for the benefits of biogenic carbon storage during its storage *per se*, i.e. at use phase (instead of the point of emission at incineration on EoL), avoiding the need for EoL allocation on biogenic flows.

The results of this article may support the role of policy makers in function to circular economy policies. It focused on highlighting the variability of (biogenic) carbon footprint calculation of wood cascade products in LCA. In order to recommend the best options for BCA methods and EoL allocation methods, in the context of wood cascade systems, a more robust analysis should be performed.

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