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Wood substitution potential in greenhouse gas emission reduction–*review on current state and application of displacement factors*

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Abstract

Background: Replacing non-renewable materials and energy with wood offers a potential strategy to mitigate climate change if the net emissions of ecosystem and technosystem are reduced in a considered time period. Displacement factors (DFs) describe an emission reduction for a wood-based product or fuel which is used in place of a non-wood alternative. The aims of this review were to map and assess DFs from scientific literature and to provide findings on how to harmonise practices behind them and to support coherent application.

Results: Most of the reviewed DFs were positive, implying decreasing fossil GHG emissions in the technosystem. The vast majority of the reviewed DFs describe avoided fossil emissions either both in processing and use of wood or only in the latter when wood processing emissions were considered separately. Some of the reviewed DFs included emissions avoided in post-use of harvested wood products (HWPs). Changes in forest and product carbon stocks were not included in DFs except in a few single cases. However, in most of the reviewed studies they were considered separately in a consistent way along with DFs.

DFs for wood energy, construction and material substitution were widely available, whereas DFs for packaging products, chemicals and textiles were scarce. More than half of DFs were calculated by the authors of the reviewed articles while the rest of them were adopted from other articles.

Conclusions: Most of the reviewed DFs describe the avoided fossil GHG emissions. These DFs may provide insights on the wood-based products with a potential to replace emissions intensive alternatives but they do not reveal the actual climate change mitigation effects of wood use. The way DFs should be applied and interpreted depends on what has been included in them. If the aim of DFs is to describe the overall climate effects of wood use, DFs should include all the relevant GHG flows, including changes in forest and HWP carbon stock and post-use of HWPs, however, based on this literature review this is not a common practice.

DFs including only fossil emissions should be applied together with a coherent assessment of changes in forest and HWP carbon stocks, as was the case in most of the reviewed studies. To increase robustness and transparency and to decrease misuse, we recommend that system boundaries and other assumptions behind DFs should be clearly documented.

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Background

Forests and soils have a crucial role in climate change mitigation as major carbon sinks removing approximately one quarter or third of CO_2 emitted to the atmosphere (Le Quéré et al., 2018). Besides of that, forests provide renewable materials and energy which can be used in place of non-renewable materials and energy. Substitution effects caused by replacing emission-intensive materials with increased production of wood products and fuels offers a potential strategy to decrease greenhouse gas (GHG) concentrations emissions into the atmosphere (Werner et al. 2010; Hagemann et al. 2016; Geng et al. 2017a). In most cases the manufacturing of wood products and fuels causes less emissions compared to non-wood alternatives (e.g. Sathre and O'Connor 2010; Rüter et al. 2016; Leskinen et al. 2018). However, increasing wood harvests reduces the amount of carbon sequestered and stored in forests at least for decades, thus resulting in trade-off between carbon sequestration and substitution (Helin et al. 2013).

Recently the substitution potential of wood products and fuels has been under an active scientific and political discussion (e.g. Geng et al. 2017a; Werner et al. 2010). The climate change mitigation potential of wood products needs to be considered comprehensively to include all relevant factors, in particular impacts on forest ecosystems including changes in carbon storages in the trees and soil of forest, GHG emissions due to forest management operations, changes in carbon stock in harvested wood products (HWPs), and potentially avoided emissions when substituting alternative materials and energy (Geng et al. 2017a). In the forest ecosystem, CO_2 is uptaken through photosynthesis and emitted through respiration into the atmosphere. Carbon is stored in above- and below-ground stocks of forests which are reduced by harvesting and increased by wood growth and litter input. Harvested wood biomass is transferred to technosystem in which carbon is stored in wood products over their lifetime. GHG emissions from fossil fuels are generated from the production and use of alternative materials and energy and typically also in different life cycle stages of wood products, such as harvesting, transportation, processing, use and end-of-life treatment. In order to mitigate climate change by increasing the use of HWPs in place of alternative products, the change in net GHG emissions of ecosystem and technosystem should be negative over a given time horizon. Avoided fossil GHG emissions through substitution and carbon stored in HWPs should be higher than carbon loss in a forest due to increased wood harvesting during a given time frame.

Displacement factors to assess displacement potential of wood products

One relevant factor in an assessment of change in net GHG emissions caused by wood utilisation is determination of avoided emissions via product and fuel substitution. A displacement factor (DF) describes the efficiency of using wood products and fuels in reducing GHG emissions by quantifying the amount of emission reduction achieved by wood use (Sathre and O'Connor 2010). Wood and non-wood products should have the same functionality. The GHG emissions of compared products are often calculated according to the rules of Life Cycle Assessment (ISO 14040) and the avoided GHG emissions caused by wood products are obtained from the difference of GHG emissions between wood and non-wood products. A positive DF implies that the wood products would decrease GHG emissions, whereas negative value implies the opposite.

According to Sathre and O'Connor (2010), DF can be aggregated as follows

$$DF = \frac{GHG_{non-wood} - GHG_{wood}}{WU_{wood} - WU_{non-wood}} \quad (1)$$

$GHG_{non\text{-}wood}$ and GHG_{wood} include aggregated GHG emissions of non-wood and wood products, and WU_{wood} and $WU_{non\text{-}wood}$ describe the amounts of wood (in carbon tons) used in the wood and non-wood products. $WU_{non\text{-}wood}$ can be more than zero in a case of e.g. concrete-framed buildings with roof structures, doors or window frames made of wood (Sathre and O'Connor 2010). According to Sathre and O'Connor (2010), DFs could be calculated in other units as well, e.g., emission reduction per ton of wood product, or per m^3 of wood product, or per m^3 of roundwood, or per hectare of forestland but t C/t C appears to be the most transparent and comparable option. Because both emission reduction and wood use are expressed in the same unit DF is an elegant indicator of the "multiplicative" effect of using wood products for GHG mitigation (Sathre and O'Connor 2010). Leskinen et al. (2018) pointed out that there are at least two approaches to calculate wood used in wood products. In the first approach, WU includes only the wood contained in end-use products. In the second approach, WU includes all harvested wood used for producing a wood end-product. Leskinen et al. (2018) concluded that the both approaches are acceptable, but they lead to different calculation rules in the assessment of substitution effects.

A meta-analysis with 51 studies conducted by Leskinen et al. (2018) produced a range for DFs between − 0.7 and 5.1 t C/t C (including 95% of observed values). They divided construction sector into two product categories: structural construction (e.g. building, internal or external wall, wood frame, beam) and non-structural construction. Their respective ranges were between − 0.9 and 5.5 t C/t C and 0.2 and 4.7 t C/t C. For textiles, the DF in their meta-analysis was 2.8 t C/t C and for other product categories (e.g. chemicals, furniture, packaging) the range was 1–1.5 t C/t C. Meta-analysis by Sathre and O'Connor (2010) generated DFs for construction from − 2.3 to 15 t C/t C, with an average value of 2.1 t C/t C. Substituting materials appears to be more effective in reducing GHG emissions than substituting fuels (Geng et al. 2017a). In most of these previous studies, it seems that wood use decreases GHG emissions. Although these studies give insights on the substitution effects of wood use, they do not provide a holistic analysis on the application of DFs. Currently, there are no well-accepted rules how to determine and apply DFs.

Estimating the net GHG emissions of wood substitution is a complex undertaking requiring consideration of several factors. Leskinen et al. (2018) concluded that DFs do not provide sufficient information to guide policy making as consideration of forest and forest soil sinks, HWP carbon storage, permanence of forest sinks and forest disturbances, and potential carbon leakage effects is also required. However, systematic studies on how DFs are applied, and how the fossil and biogenic carbon flows are considered in DFs, are not currently available. Although there are moderately clear definitions for DF, different methodological choices under the definitions are possible making it difficult to compare and apply DFs. As wood substitution and DFs is considered a timely and highly important topic in terms of the climate change mitigation potential of wood products and wood-based bioeconomy, more systematic work is needed to detect the current state in the development of DFs.

This study provides a review on DFs and their application in the scientific literature. We assess how comprehensive DFs are considering current wood-based products and wood use scenarios in the future. Based on a systematic literature review, a sample of DFs is evaluated according to several criteria, which are considered relevant for the application of DFs. The assessment criteria include determination of the originality of DFs, i.e. if the aggregation of DFs are actualised by the authors of the reviewed studies or if DFs are adopted from other studies. We also consider which carbon flows are considered and how they are allocated. First, we consider if the biogenic carbon flows are included into DFs or if they are considered separately. The relevant biogenic carbon flows include 1) carbon loss in forests because of harvesting and consequent wood use, and 2) carbon stored in HWPs. Also inclusion of fossil-based emission in wood product processing are considered. Furthermore, we evaluate if post-use of HWP (energy recovery or landfilling) is included in DF. We critically assess the approaches used to develop DFs and their transparency. Based on our review we give recommendations on how to develop and report DFs in a more transparent and holistic manner and how they should be applied and understood coherently.

Material and methods

Our aim was to assess DFs applied in the scientific literature (using databases Science Direct, Springer Link, Pubmed and Web of Science). The combination of searched keywords was as follows: "displacement factor AND/OR substitution factor AND HWP AND substitution". Only research articles and scientific reports which included clearly defined DFs were included in this review. Review articles and meta-analyses on DFs were not included.

All relevant studies were carefully reviewed in order to detect how the DFs were determined and what key assumptions were included in them. First, we mapped whether DFs presented in reviewed studies were based on some earlier studies or determined by the authors of the reviewed studies. Secondly, we analysed DFs against key assumptions for which we separate 1) changes in forest carbon stock, 2) changes in HWP carbon stock, 3) post-use of HWPs, and 4) fossil fuel input in HWP processing. Finally, the overall application and applicability of DFs were evaluated based on consideration of these key assumptions.

Displacement factors in the scientific literature

As a result of this systematic review, we identified 37 journal articles and scientific reports that included 149 DFs altogether (Table 1). The DFs were divided into four groups: energy, construction, other products and material use (Fig. 1). Most of the journal articles and research reports were published quite recently (2015–2020). Majority of DFs were country-specific, with more than 30 DFs for Germany (Fig. 2). Time frames considered when assessing substitution effects in these studies were moderately long. Majority of studies included a time frame of at least 30 years. Only few studies considered the substitution effects for a single year (e.g. Suter et al. 2017; Geng et al. 2019) or considered the past trends (e.g. Ji et al. 2016).

The most common approach to define a DF was to consider avoided carbon (or CO_2 equivalents) per embodied carbon. In some cases, the emission reduction potential was estimated per mass unit of wood, timber, per m^3, m^2 or per harvested wood. Thus, various units to identify substitution potential of wood use were applied in the scientific literature.

We estimated that about half of the studies reviewed had obtained DFs from certain previous research, whereas the rest of the DFs were based on authors' own calculations (Table 1). The papers with DFs calculated by the authors included more DFs than papers where

Table 1 Journal articles and scientific reports including application of DFs as a result of a literature review. The assessment was separated to consideration of DF source and inclusion of some key factors in DFs or separately from them, Yes refers to Included, No (E) refers to Excluded and No (CS) refers to considered separately

Authors	DF source	Countries/ Time series considered	Included in DF			
			Forest C	HWP C	Post-use of HWP	Fossil fuel input in wood processing
Fortin et al. (2012)	FCBA (2009a, 2009b); Hischier (2007); and Puettmann and Wilson (2005)	France/ 250 years	No (E)	No (CS)	No (CS)	No (CS)
Böttcher et al. (2012)	Petersen and Solberg (2005); Dornburg and Faaij (2005)	Germany/ 300 years	No (CS)	No (CS)	No (CS)	Yes
Smyth et al. (2014)	own calculations	Canada/ 2015–2050	No (CS)	No (CS)	No (E)	Yes
Knauf et al. (2015)	own calculations	Germany/ 2011–2050 and 2100	No (CS)	No (CS)	No (CS)	Yes
Soimakallio et al. (2016)	own calculations	Finland/ 100 years from 2010	No (CS)	No (CS)	No (CS)	No (CS)
Knauf (2016)	Knauf et al. (2015)	Germany/ 2011–2100	No (E)	No (CS)	No (CS)	Yes
Han et al. (2016)	Adopted from Chung et al. (2013)	South Korea/ 280 years	No (CS)	No (CS)	No (CS)	No (CS)
Matsumoto et al. (2016)	Noda et al. (2016); Kayo et al. (2011) Japan Environmental Management Association for Industry (2014)	Japan/ 2010–2050	No (CS)	No (CS)	No (CS)	Yes
Cintas et al. (2016)	own calculations	Sweden/ 300 years	No (CS)	No (CS)	Yes	No (CS)
Smyth et al. (2017a)	own calculations	Canada/ 2015 to 2050	No (CS)	No (CS)	No (E)	Yes
Härtl et al. (2017)	Rüter (2011) and Rock and Bolte (2011)	Germany/ 2015–2040	No (CS)	No (CS)	Yes	Yes
Schweinle et al. (2018)	Knauf (2015)	Germany/ 2013–2208	No (CS)	No (CS)	No (CS)	Yes
Smyth et al. (2017b)	own calculations	Canada/ 2017 to 2050	No (CS)	No (CS)	No (E)	Yes
Ji et al. (2016)	own calculations	China/ 1960–2014	No (E)	No (CS)	No (E)	No (CS)
Baul et al. (2017)	own calculations	Finland/ 2016–2055	No (CS)	No (CS)	Yes/No (E)	Yes
Suter et al. (2017)	own calculations	Switzerland/ 2011	No (E)	No (CS)	Yes	Yes
Chen et al. (2018)	own calculations	Canada/ 100 years	No (CS)	No (CS)	No (E)	Yes
Smyth et al. (2018)	Smyth et al. (2016)	Canada/ 2018 to 2050	No (CS)	No (CS)	No (E)	Yes
Köhl et al. (2020)	own calculations	Germany/ 2013 to 2015	No (CS)	No (CS)	Yes/No (E)	Yes
Hurmekoski et al. (2020)	own calculations	Finland/ 2015–2056	No (CS)	No (CS)	Yes	Yes
Buchanan and Levine (1999)	own calculations	New Zealand/ not specified	No (E)	No (E)	No (E)	Yes
Nepal et al. (2016)	based on estimates from Sathre and O'Connor (2010)	United States/ 2010–2060	Yes /No (CS)	No (CS)	No (E)	Yes
Rüter et al. (2016)	own calculations	Europe/ 2000–2030	No (CS)	No (CS)	Yes	Yes
Geng et al. (2017b)	own calculations	not specified	No (E)	Yes/ No (E)	Yes/No (E)	Yes
Härtl et al. (2017)	Rüter (2011) and Rock and Bolte (2011)	Germany/ 2010–2040	No (CS)	No	Yes	Yes

Table 1 Journal articles and scientific reports including application of DFs as a result of a literature review. The assessment was separated to consideration of DF source and inclusion of some key factors in DFs or separately from them, Yes refers to Included, No (E) refers to Excluded and No (CS) refers to considered separately *(Continued)*

Authors	DF source	Countries/ Time series considered	Included in DF			
			Forest C	HWP C	Post-use of HWP	Fossil fuel input in wood processing
				(CS)		
Xu et al. (2018)	Smyth et al. (2016)	Canada/ 2017–2050	No (CS)	No (CS)	No (CS)	Yes
Keith et al. (2015)	Sathre and O'Connor (2010)	Australia/ 20, 50 and 100 year periods	No (CS)	No (CS)	No	Yes
Macintosh et al. (2015)	Sathre and O'Connor (2010)	Australia/ 2013–2113	No (CS)	No (CS)	No (E)	No (CS)
Knauf et al. (2016)	own calculations	Germany/ 2011–2100	No (E)	No (CS)	No (CS)	Yes
Butarbutar et al. (2016)	Sathre and O'Connor (2010)	Not specified/ 2010	No (CS)	No (CS)	Yes/No (E)	Yes
Taeroe et al. (2017)	Sathre and O'Connor (2010)	Denmark/ 200 years	No (CS)	No (CS)	No (CS)	Yes
Lobianco et al. (2016)	Sathre and O'Connor (2010)	France/ 2007–2100	No (CS)	No (CS)	No (CS)	Yes
Seppälä et al. (2019)	own calculations	Finland/ 100 years	No (CS)	No (CS)	Yes	Yes
Olguin et al. (2018)	Sathre and O'Connor (2010); Smyth et al. (2014, 2016)	Mexico/ 2010–2050	No (CS)	No (CS)	No (E)	Yes
Kayo et al. (2015)	own calculations	Japan/ 2010–2050	No (E)	No (CS)	No (CS)	Yes
Geng et al. (2019)	own calculations	China/ 2015	No (E)	No (E)	No (E)	Yes
Chen et al. (2014)	own calculations	Canada/ 1901–2010	No (E)	No (CS)	No (CS)	No (CS)

the DFs were adapted from previous studies. Thus, the majority of DFs in this review were based on the calculations of the authors of the original journal articles and research reports.

Changes in forest and HWP carbon stocks were not included in DFs except in single cases (Table 1). Nepal et al. (2016) included changes in forest carbon stock due to harvest of energy wood in DFs. Geng et al. (2017b) included HWP carbon stock as offset emissions in the DFs in their basis scenario. In most of the studies changes in forest and HWP carbon stocks were considered separately. Consideration of post-use of HWPs and avoided emissions due to reuse or energy recovery at the end of life varied between studies; some included, some considered separately, while some excluded (Table 1). Most of the studies included GHG emissions due to fossil

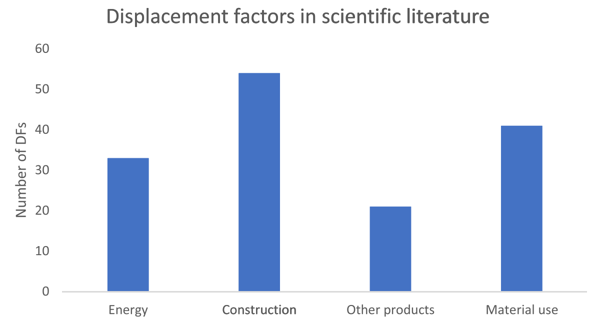

Fig. 1 DFs in scientific literature

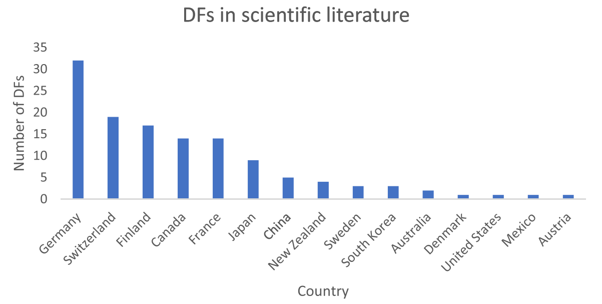

Fig. 2 Country specific DFs in scientific literature

energy requirement in wood processing in DFs, while some considered it separately from DFs.

In the next paragraphs we assess DFs more specifically considering special features of energy, construction, other wood products and material use of wood.

Displacement factors for energy substitution

Altogether 33 DFs for energy use were retrieved from scientific literature (Table 2). Majority of energy DFs were based on calculations of the authors of those research articles. A substitution rate of 0.8 t C/t C has been widely used in the literature, implying that GHG emissions from fossil fuels are reduced by 80% of the carbon content of biofuel (see references in Pukkala (2014)). However, most of the DFs in the scientific literature (Table 1) are lower than 0.8 t C/t C, designating that all wood-based fuels do not replace fossil energy or they replace fossil energy with low emissions. Negative DFs have also been identified, implying increasing fossil GHG emissions (Smyth et al. 2014). In the study by Smyth et al. (2014), the wide range of DFs resulted from differences in original energy sources in different regions of Canada, indicating that substituted energy source is a highly influential factor when determining a DF. When the energy source to be substituted is estimated to have higher GHG emission intensity than for instance, an average energy mix including renewable energy sources, the DF is higher (Smyth et al. 2014; Ji et al. 2016). Consequently, DF can be negative or positive, depending on substituted fuel type (Caurla et al. 2018). Naturally, emissions of wood based energy is also an influential factor. GHG emission of wood-based energy, such as lignite, can be much higher than emissions of e.g. natural gas (Knauf et al. 2016).

Displacement factors for construction substitution

Most of the DFs in the scientific literature (Table 3) are related to construction sector (55 DFs). In Rüter et al. (2016) some negative DFs for construction products were identified (for parquets and insulation), implying that the substitution would in fact increase fossil GHG emissions in the technosystem. Also Suter et al. (2017) determined a close to zero DF for insulation materials. Authors of two journal articles (Knauf et al. 2015; Geng et al. 2017b) estimated, unlike Rüter et al. (2016) that the use of wood-based flooring in place of flooring materials such as laminate and ceramics would decrease fossil GHG emissions.

The functional equivalency of construction materials to be substituted is crucial. In few cases, DF was determined for a building (e.g. Kayo et al. 2015) but also DFs for construction materials were determined (Table 3). Determination of functional equivalency is, however, not straightforward. For example, wooden structures may be used in place of concrete structures in buildings (e.g. Sandanayake et al. 2018). The choice between wooden and concrete structures may, however, influence on the other material requirements or the energy consumption of buildings. Consequently, DF calculated for a wood material used in a building without taking the volumes of different products may look different than DF calculated for the whole building. Only very few wood products such as window frames can replace non-wood products with the same functionality (e.g. same insulation character in the case of window frames) in the whole building systems (e.g. Rüter et al. 2016). Contained wood in buildings depends for example on the planning solutions, and the dependency of different material amounts are complicated and they vary within the same functionality requirements of a building (e.g. European Committee for Standardization 2012; International Organization for Standardization 2017).

Displacement factors for other wood-based products

For other wood-based products 21 DFs were identified, vast majority of them being based on calculations of the authors of the original research articles. This group of wood-based products included some DFs with a substantial fossil GHG emission reduction potential (Table 4). Some product groups such as packaging and textiles have not been given much attention in research articles and scientific reports focusing on substitution effects. For packaging products only four DFs have been determined and the situation is almost the same for textiles. For wood-based chemicals only one DF was found for polyol (Rüter et al. 2016). Only three groups of authors have determined DF for packaging replacing plastics and metals (Knauf et al. 2016; Soimakallio et al. 2016; Hurmekoski et al. 2020). Wood-based packaging is estimated to increase not only because of increasing consumption, but because wood-based packaging is estimated to replace other packaging materials such as plastics (Koskela et al. 2014). Furthermore, wood-based composites are one potential packaging material (Sommerhuber et al. 2017). Only one DF for wood-based composites in car manufacturing was found (Hurmekoski et al. 2020).

The global viscose staple fiber market valued at 5594 kt in 2017 and the amount is expected to increase in the future (Global Viscose Staple Fiber Market 2018). The main reason for the growth is an increased consumption of textile apparel coupled with the limited growth potential of cotton and land-use competition. The benefits could be quantified by a DF. Such a DF was found, however, only in Rüter et al. (2016) (4.53 kg CO_2-eq./kg HWP, with a decreasing trend) and Hurmekoski et al. (2020) (4.0 t C/t C).

Table 2 DFs for energy substitution identified in scientific literature

Energy DFs

Authors	**Country**	**Description**	**DF**	**Unit**
Fortin et al. (2012)	France	Domestic energy wood and industrial wood pellets replace electricity and oil	0.076	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Wood pellets	0.126	Mg/m^3 of C eq.
Böttcher et al. (2012)	Germany	Substituting heating oil by biomass	0.8	Fossil fuel-C substituted/tonne biofuel-C harvested
Smyth et al. (2014)	Canada	Domestic bioenergy	−0.08–0. 79	Mg C/Mg C
Smyth et al. (2014)	Canada	International bioenergy	0.6	Mg C/Mg C
Knauf et al. (2015)	Germany	Fuel substitution	0.67	t C/t C
Soimakallio et al. (2016)	Finland	Substitution factor for paper products (fossil fuel substitution)	0.8	t C/t C
Soimakallio et al. (2016)	Finland	Substitution factor for paperboard products (plastics, fossil fuel substitution)	1.40	t C/t C
Soimakallio et al. (2016)	Finland	Substitution factor for energy and post-used mechanical wood products (fossil fuel substitution)	0.47–0.89	t C/t C
Knauf (2016)	Germany	Fuel substitution	0.67	t C/t C
Knauf et al. (2016)	Germany	Fuel substitution	0.67	t C/t C
Han et al. (2016)	South Korea	Sawnwood and industrial roundwood substituting fossil fuels for heating purposes	0.076	Mg/m^3 C eq.
Han et al. (2016)	South Korea	Wood pellets and industrial roundwood substituting fossil fuels for heating purposes	0.126	Mg/m^3 C eq.
Matsumoto et al. (2016)	Japan	Logging residues, process residues and waste wood; Substitution of residues and waste wood for heavy oil kg	108.9	$kg C/m^3$
Cintas et al. (2016)	Sweden	Forest-based bioenergy	0.55–1.27	Mg of fossil C is displaced/Mg of C in biomass used
Smyth et al. (2017a)	Canada	Bioenergy from harvest residues	0–2	t C/t C
Härtl et al. (2017)	Germany	Timber used in energy production	0.67	$t C_{fossil}/t C_{timber}$
Smyth et al. (2017b)	Canada	Bioenergy using an optimized selection of bioenergy facilities which maximized avoided emissions from fossil fuels.	0.47–0.89	t C/t C
Ji et al. (2016)	China	Substitute for Coal	0.96	t C/t C
Ji et al. (2016)	China	Substitute for Oil	0.79	t C/t C
Ji et al. (2016)	China	Substitute for Natural Gas	0.56	t C/t C
Baul et al. (2017)	Finland	Energy biomass	0.5	t C/t C
Suter et al. (2017)	Switzerland	Heat replacing light fuel oil	0.55	$t CO_2$-eq/m^3
Suter et al. (2017)	Switzerland	Heat replacing natural gas	0.32	$t CO_2$-eq/m^3
Suter et al. (2017)	Switzerland	Electricity mix CH	0.12	$t CO_2$-eq/m^3 wood
Schweinle et al. (2018)	Germany	Displacement of fossil fuel with wood fuel	0.67	t C/t C
Chen et al. (2018)	Canada	Wood used to produce energy for the HWP industry reduced fossil fuel-based emissions	2.00	$t CO_2$ eq/t C in wood
Smyth et al. (2018)	Canada	Collected harvest residues for bioenergy, energy demand and displacement factors two forest management unit	0.38, 0.95	t C/t C

Table 2 DFs for energy substitution identified in scientific literature *(Continued)*

Energy DFs				
Authors	**Country**	**Description**	**DF**	**Unit**
Köhl et al. (2020)	Germany	Lignite substitution in order to achieve carbon neutrality	1.9	t C/t C
Köhl et al. (2020)	Germany	Gas substitution in order to achieve carbon neutrality	2.5	t C/t C
Hurmekoski et al. (2020)	Finland	Wood use replacing CHP of fossil origin	0.7	t C/t C
Hurmekoski et al. (2020)	Finland	Wood-based transport fuel replacing diesel	0.63	t C/t C
Hurmekoski et al. (2020)	Finland	Wood-based ethanol replacing transport fuel	0.7	t C/t C

Displacement factors for material use

Many DFs are defined for wood material use, such as sawn wood, timber and panels, without specifying the end uses (Table 5). Some journal articles and scientific reports defined a single DF for all types of wood material uses (e.g. Knauf 2016; Lobianco et al. 2016). DFs for panel and sawn wood were sometimes defined separately (e.g. Smyth et al. 2014), but in some cases they were both included in a single DF with an uncertainty range (Soimakallio et al. 2016). Knauf et al. (2015) had determined a higher DF for sawn wood than panel, whereas Smyth et al. (Smyth et al. 2014) had a higher DF for panels than for sawn wood.

Discussion

Assessment of net GHG balance of wood use

Majority of reviewed DFs were positive, implying that wood use is decreasing GHG emissions. This does not reveal, however, the actual climate mitigation effect of wood use as consideration of biogenic carbon flows is required (Fig. 3). Still, these DFs may provide insights on the wood-based products with a potential to replace emissions intensive alternatives. Changes in forest and HWP carbon stocks were excluded from DFs in almost all the reviewed studies (Table 1). This has two important implications. First, exclusion of changes in forest and HWP carbon stocks make DFs not subjective to these uncertain and dynamic flows. Second, although this may be considered as an advantage, coherent assessment of net GHG emissions of wood use requires that DFs are attached with a consistent assessment of changes in forest and HWP carbon stocks. This is the case with most of the reviewed studies. However, in some studies forest carbon stock changes were excluded (Table 1). In some cases this was due to the fact that DFs were attached with absolute forest carbon flows representing certain forest management scenario. Such an assessment excludes the fact that substitution is always relative to the reference scenario in which wood use studied would have not taken place but the alternative products serving the equivalent functions compared to wood products would have taken place (Koponen et al. 2018). Increasing harvest rates to provide more wood to technosphere to substitute fossil GHG emissions typically reduces carbon sequestration into forests, which is only partly offset by an increase in HWP carbon stock (Soimakallio et al. 2016; Seppälä et al. 2019). Consequently, exclusion of changes in forest and HWP carbon stocks results in misunderstandings, probably overestimations, of climate benefits of wood use, particularly in the short term.

On the key methodological choices and data causing variability in displacement factors

Number of assumptions are required to determine a DF. Even though the key factors, including consideration of changes in forest and HWP carbon stocks, end-of-life treatment of HWPs and fossil energy input in wood processing, were known when determining and applying DFs, yet there are many other assumptions that may influence DFs. Differences in conversion units, methodological choices, system boundaries, allocation procedures, functional units, and case-specific factors related to processes and energy sources are all relevant. In many cases DFs are directly derived from earlier literature or somehow adjusted by the authors of the original studies. This implies that the scientific literature on DFs widely rely on a limited amount of data. Especially the review by Sathre and O'Connor (2010) was cited frequently, in particular regarding wood construction. However, their meta-analysis included only a few case studies with a small sample of different house types. Based on our review, it is not clear if all these methodological choices were considered and what the influence of various choices would have been. This raises issues not only in comparing DFs between various studies and equivalent functional unit but also on the applicability of DFs to study the net GHG emissions of wood use.

Consideration of end-of-life treatment of wood-based products varied between studies (Table 1). The end-of-life treatment of wood-based product can be a highly

Table 3 Displacement factors for construction

Construction DFs				
Authors	**Country**	**Description**	**DF**	**Unit**
Buchanan and Levine (1999)	New Zealand	Concrete to wood, hostel	1.05	Reduced emission carbon by the increase in stored carbon
Buchanan and Levine (1999)	New Zealand	Concrete to wood, office	1.10	Reduced emission carbon by the increase in stored carbon
Buchanan and Levine (1999)	New Zealand	Steel to wood, industry	1.60	Reduced emission carbon by the increase in stored carbon
Buchanan and Levine (1999)	New Zealand	Concrete, steel to wood, houses	2.1–15	Reduced emission carbon by the increase in stored carbon
Fortin et al. (2012)	France	Truss and flooring	0.169	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Exterior cladding	0.024	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Interior coverings	0.024	Mg/m^3 of C eq.
Fortin et al. 2012)	France	Other end-use products	0.024	Mg/m^3 of C eq.
Böttcher et al. (2012)	Germany	Building construction *(Picea)*	0.24	t fossil fuel-C substituted/t of wood-C harvested
Böttcher et al. (2012)	Germany	Building construction *(Fagus)*	0.16	t fossil fuel-C substituted/t of wood-C harvested
Chen et al. (2014)	Canada	Wood replacing houses with fossil raw materials (steel, concrete)	2.40	t C/t C
Knauf et al. (2015)	Germany	Roundwood (poles, fences, buildings, also treated) vs. steel, concrete, aluminum	2.40	t C/t C
Knauf et al. (2015)	Germany	Softwood lumber, sawn, wet, for packaging concrete shuttering vs. plastics (foils, 3-D elements)	1.80	t C/t C
Knauf et al. (2015)	Germany	Softwood lumber, planned and dried for building Purposes	1.40	t C/t C
Knauf et al. (2015)	Germany	Softwood based glued timber products (glue-lam, CLT) vs.	1.30	t C/t C
Knauf et al. (2015)	Germany	Plywood, also overlaid vs. aluminum profiles, glass-fiber plastic	1.62	t C/t C
Knauf et al. (2015)	Germany	Wood-based panels like particleboard, MDF, OSB (for walls, ceilings, roofs) vs. gypsum board, plaster, concrete, brick type walls	1.1	t C/t C
Knauf et al. (2015)	Germany	DIY products like lumber, panels, profile boards vs. mineral	1.35	t C/t C
Knauf et al. (2015)	Germany	Wooden flooring (one layer, multi layers), laminate flooring vs. ceramic tiles, plastic flooring, wall to wall carpet	1.35	t C/t C
Knauf et al. (2015)	Germany	Doors (interior, exterior) – only framing/construction vs. steel, aluminum, PVC	1.62	t C/t C
Knauf et al. (2015)	Germany	Wooden window frames vs. PVC, aluminum	1.62	t C/t C
Knauf et al. (2015)	Germany	Wooden furniture (solid wood) vs. glass, plastic, metal	1.62	t C/t C
Knauf et al. (2015)	Germany	Wooden furniture (panel based) vs. glass, plastics, metal	1.42	t C/t C
Knauf et al. (2015)	Germany	Wooden kitchen furniture vs. glass, plastics, metal	1.62	t C/t C
Knauf et al. (2015)	Germany	Wooden transportation products vs. plastic, metal	1.62	t C/t C
Kayo et al. (2015)	Japan	Building construction: substitution of wooden buildings for non-wooden buildings	60.56	kg C/m^2

Table 3 Displacement factors for construction *(Continued)*

Construction DFs

Authors	Country	Description	DF	Unit
Kayo et al. (2015)	Japan	Civil engineering: substitution of wooden piles for cement and sand piles	46.77	kg C/m^3
Kayo et al. (2015)	Japan	Civil engineering: substitution of wooden guardrails for metal guardrails	64.48	kg C/m^3
Kayo et al. (2015)	Japan	Furniture: substitution of wooden furniture for metal furniture	43.17	kg C/m^3
Nepal et al. (2016)	United States	Extra wood products used in nonresidential construction buildings	2.03	Ton CO$_2$e/t CO$_2$e
Rüter et al. (2016)	Europe	Core and shell 2010	1.58	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Core and shell 2030	1.25	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Insulation 2010	−0.40	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Insulation 2030	−0.32	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Windows 2010	5.53	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Windows 2030	4.42	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Claddings 2010	0.9	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Claddings 2030	0.72	kg CO$_2$-eq./kg HWP
Rüter et al. 2016)	Europe	Laminates 2010	1.52	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Laminates 2030	1.22	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Parquets 2010	−0.0164	kg CO$_2$-eq./kg HWP
Rüter et al. (2016)	Europe	Parquets 2030	−0.0131	kg CO$_2$-eq./kg HWP
Matsumoto et al. (2016)	Japan	Sawnwood and plywood; substitution of wooden buildings for non-wooden buildings	301.30	kg C/m^3
Matsumoto et al. (2016)	Japan	Roundwood and sawnwood; substitution of wooden piles for cement and sand piles	46.8	kg C/m^3
Matsumoto et al. (2016)	Japan	Roundwood and sawnwood; substitution of wooden guardrails for metal guardrails	64.5	kg C/m^3
Matsumoto et al. (2016)	Japan	Sawnwood and plywood; substitution of wooden furniture for metal furniture	43.2	kg C/m^3
Geng et al. (2017b)	China	Ceramic tile replaced with wood flooring	0.17–0.78	tC/m^3
Härtl et al. (2017)	Germany	Timber as sawnlogs used in construction	1.66	t C$_{fossil}$/t C$_{timber}$
Xu et al. (2018)	Canada	Sawnwood for single-family home, multi-family home, and multi-use building	2.10	t C/t C
Xu et al. (2018)	Canada	Panels for single-family home, multi-family home, and multi-use building	2.20	t C/t C
Chen et al. (2018)	Canada	Residential contruction	9.56	t CO$_2$ eq emissions reduced per tonne of C
Chen et al. (2018)	Canada	Non-residential construction	3.64	t CO$_2$ eq emissions reduced per tonne of C
Geng et al.	China	Furniture sector	1.46	t C/t C

Table 3 Displacement factors for construction *(Continued)*

Construction DFs

Authors	**Country**	**Description**	**DF**	**Unit**
(2019)				
Hurmekoski et al. (2020)	Finland	Sawnwood in construction	1.1	t C/t C
Hurmekoski et al. (2020)	Finland	Plywood in construction	1.1	t C/t C

influential factor as there are various alternative treatment options for discarded products. One extreme is that HWPs are incinerated at the end of life without energy recovery (e.g. Han et al. 2016) while another extreme is that they are reused to substitute alternative material (e.g. Rüter et al. 2016) or energy (e.g. Hurmekoski et al. 2020). It should be noted that material or energy recovery at the end of life generates additional substitution credits only if the material substituted at the first place cannot serve the same function at the end of

Table 4 Displacement factors for other products

Other products DFs

Authors	**Country**	**Description**	**DF**	**Unit**
Härtl et al. (2017)	Germany	Paper, cardboard and chipboard replace plastics	1.30	t C fossil/t C timber
Knauf et al. (2015)	Germany	Wood-based packaging	1.35	t C/t C
Fortin et al. (2012)	France	Wood replaces steel in heavy packaging	0.0117 (sawlog part), 0.0621 (panel board part)	t C/t C Mg/m^3 of C eq.
Fortin et al. (2012)	France	Office furniture	0.043	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Kitchen furniture	0.069	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Home furniture	0.043	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Chairs	0.043	Mg/m^3 of C eq.
Fortin et al. (2012)	France	Beds	0.043	Mg/m^3 of C eq.
Rüter et al. (2016)	Europe	Pallets in 2030	0.35	kg CO_2-eq./kg HWP
Knauf et al. (2015)	Europe	Wooden transportation products vs. plastic, metal	1.62	t C/t C
Rüter et al. (2016)	Europe	Viscose replacing textiles in 2010	4.53	kg CO_2-eq./kg HWP
Rüter et al. (2016)	Europe	Viscose replacing textiles in 2030	3.62	kg CO_2-eq./kg HWP
Rüter et al. (2016)	Europe	Polyol in 2010	0.77	kg CO_2-eq./kg HWP
Rüter et al. (2016)	Europe	Polyol in 2030	0.616	kg CO_2-eq./kg HWP
Rüter et al. (2016)	Europe	Office furniture 2010	0.73	kg CO_2-eq./kg HWP
Rüter et al. (2016)	Europe	Office furniture 2030	0.58	kg CO_2-eq./kg HWP
Hurmekoski et al. (2020)	Finland	Plastic components for cars (replacing polypropylene)	7.38	t C/t C
Hurmekoski et al. (2020)	Finland	Ethylene in packaging (replacing PE, PET)	1.40	t C/t C
Hurmekoski et al. (2020)	Finland	Textiles (viscose)	4.0	t C/t C
Hurmekoski et al. (2020)	Finland	Kraft pulp based packaging (carton boards, sack paper)	1.40	t C/t C
Hurmekoski et al. (2020)	Finland	Furniture replacement	0.9	t C/t C

Table 5 Displacement factors for material use

Material use DFs				
Authors	**Country**	**Description**	**DF**	**Unit**
Smyth et al. 2014	Canada	Sawnwood	0.38	Mg C avoided/ Mg C used
Smyth et al. 2014	Canada	Panel	0.77	Mg C avoided/ Mg C used
Kalt et al. (2015)	Austria	Average DF in simulations	2.67	C/C
Knauf et al. (2015)	Germany	Average wood use as material	1.50	t C/t C
Knauf et al. (2015)	Germany	DIY products like lumber, panels, profile boards vs. mineral based products, plastic based panels, aluminum sheets	1.35	t C/t C
Knauf et al. (2015)	Germany	Wooden transportation products vs. plastic, metal	1.62	t C/t C
Keith et al. (2015)	Australia	Substitution of nonwood	2.1	t C/t C
Knauf (2015)	Germany	Average wood use as material	1.5	t C/t C
Macintosh et al. (2015)	Australia	emissions-intensive non-wood substitutes replace foregone sawnwood products	2.1	t C/t C
Knauf et al. (2016)	Germany	Material substitution	1.5	t C/t C
Butarbutar et al. (2016)	Not specified	Timber	0.8	t CO_2e/m^3 of wood product
Butarbutar et al. (2016)	Not specified	Timber and mill residues	2.1	t CO_2e/m^3 of wood product
Cintas et al. (2016)	Sweden	Sawnwood	2.31	Mg C/Mg C
Soimakallio et al. (2016)	Finland	substitution factor for sawn wood and wood-based panels (concrete, steel substitution)	1.3	t C/t C
Butarbutar et al. (2016)		Material substitution	2.1	t C/t C
Lobianco et al. (2016)	France	Material substitution	1.28	t C/t C
Han et al. (2016)	South Korea	Sawnwood and industrial roundwood substituting fossil-fuel-intensive materials, such as steel, concrete and plastics	0.04	Mg/m^3 C eq.
Taeroe et al. (2017)	Denmark	Wood product substitution	2.10	t C/t C
Baul et al. (2017)	Finland	Sawn wood	2	t C/t C
Cintas et al. (2016)	Sweden	Sawnwood	2.10	Mg C/Mg C
Smyth et al. (2017a)	Canada	sawnwood	0.54	t C/t C
Smyth et al. (2017a)	Canada	basket of end-use products included buildings	0.45	t C/t C
Suter et al. (2017)	Switzerland	Glued laminated timber substituting primary steel	0.68	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Glued laminated timber substituting secondary steel	0.14	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing concrete	0.5	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing bricks	0.37	t CO_2-eq/m^3 wood

Table 5 Displacement factors for material use *(Continued)*

Material use DFs				
Authors	**Country**	**Description**	**DF**	**Unit**
Suter et al. (2017)	Switzerland	Sawnwood products replacing polyethylene	0.85	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing aluminium, secondary	0.32	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing aluminium, primary	3.76	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing polypropylene	1.39	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing steel, chromium, secondary	1.23	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Sawnwood products replacing steel, chromium, primary	0.41	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Board, fibre substituting gypsum fibreboard	−0.31	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Board, fibre, soft subsituting rockwool	0.02	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Board, particle	0.17	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Board, particle replacint glass	0.29	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Plywood replacing chromium, secondary	1.52	t CO_2-eq/m^3 wood
Suter et al. (2017)	Switzerland	Plywood replacing chromium, primary	0.24	t CO_2-eq/m^3 wood
Olguin et al. (2018)	Mexico	Sawnwood and panels	0.45–2	t C avoided/t C used
Lobianco et al. (2016)	France	Material substitution of wood Board, fibre, soft subsituting polystyrene	1.28	t C/t C
Seppälä et al. (2019)	Finland	Required displacement factors for additional amounts of wood-based products and fuels produced from domestic wood, compared to the basic harvesting scenario	1.3–2.4	t C/t C

its life. This may be the case for example if a material with no or negative energy recovery value is displaced at the first place. In most of the cases energy recovery substitution credit was assessed separately (Fig. 3). This is a recommended approach as including energy recovery substitution credit for product DF may further cause misinterpretation on the actual substitution effect of a product.

A common LCA allocation problem related to main products and by-products has to be solved when developing DFs for wood-based products. The production of saw log, pulpwood and energy wood are often closely interconnected as sawmilling residues are used as a feedstock in pulp production and sawlogs, pulpwood and energy wood may be extracted from forest in the same harvest operations (Soimakallio et al. 2016). In addition, processing of a HWP is typically connected to one or more co-products (Fig. 4). Consequently, determination of DFs encounters a co-product treatment problem. If co-products are excluded from the system boundary where DF is determined, then GHG emissions should be allocated between the HWP studied and its co-products. The choice of allocation rule is always at least to some extent subjective (Ekvall and Finnveden 2001) and influences the value of DF. On the other hand, this choice enables to apply DFs separately for various products considering that the rule of allocation applied is known and accepted. If co-products are included in the system boundary where DF is determined, then GHG emissions avoided by co-products become an inherent part of DF of the HWP studied. In this case, co-products should not be separately credited again to avoid double-counting of the avoided GHG emissions. In several of the reviewed studies it was not completely clear how the allocation problem was solved due to lack of transparency.

Another influential choice to be made is how to consider wood flows associated with the production of

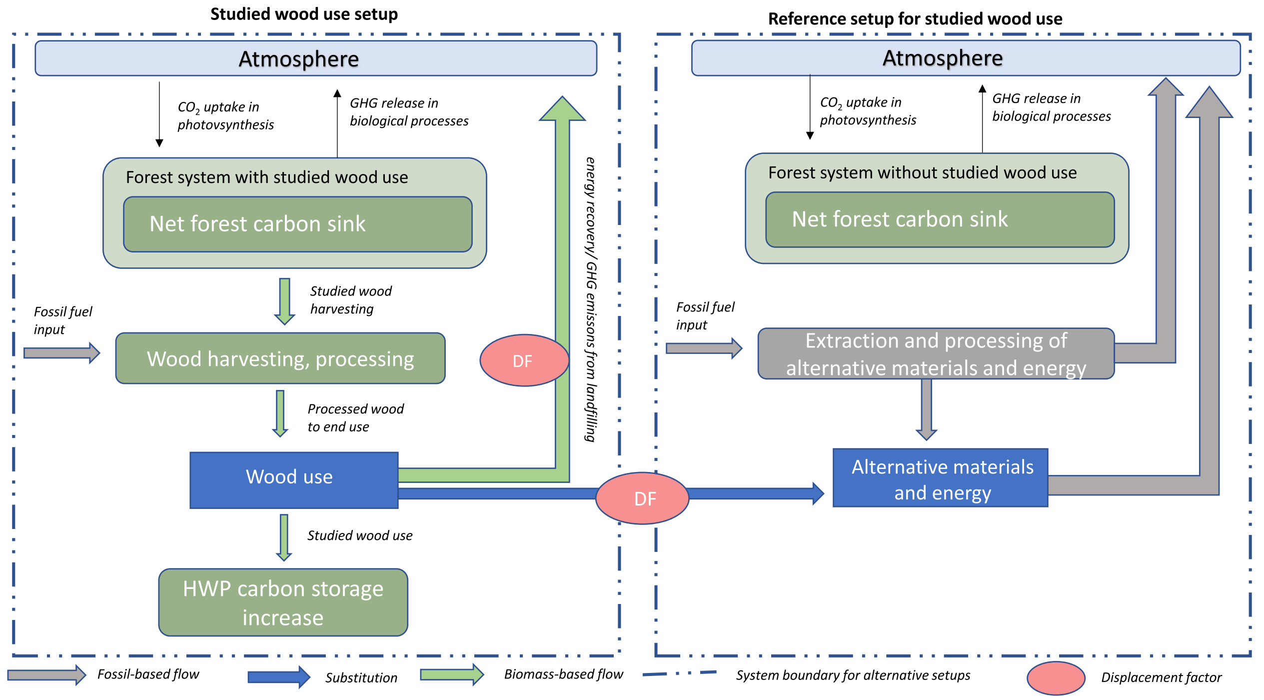

Fig. 3 Illustrative flowchart of assessment of substitution effects of wood use and the role of DFs as they are currently typically applied in scientific literature

wood-based products. If DF is determined per carbon in HWP, then the information on how much wood is used to process the product is not transparent. This may lead to inappropriately favoring those HWPs which use significant amounts of wood but little fossil fuels in their life cycle and may disfavor those HWPs which generate the most significant reduction in net GHG emissions (Schlamadinger et al. 2005; Soimakallio et al. 2009). This effect is boosted if GHG emissions avoided by co-product use are included in the system boundary of determination of DF, as shown by Sathre and O'Connor (2010). If DF is determined per carbon in wood harvested from forest then the information of wood used is naturally included and allocation between HWP studied and its co-products becomes irrelevant and GHG emissions avoided by co-product use becomes an inherent part of DF.

In most of the reviewed studies it was assumed that the DFs would not change in the future (with exceptions made by e.g. Rüter et al. 2016; Hurmekoski et al. 2020). However, the substitution effects are likely to change over time. If world is successful in climate change mitigation, global energy production will undergo rapid transformation to lower emission intensities reducing the carbon footprints of all products which use energy either directly or indirectly. As many HWPs are currently produced using wood as energy, their potential to decrease energy-originated emissions is lower than for substituted products. For instance, in the Nordic countries pulp production is based on black liquor recovery and renewable energy, which has already decreased fossil-based GHG emissions of pulp and paper production significantly (Sun et al. 2018). Sawmills use substantial amounts of energy but the share of renewable fuels used for energy generation varies in different countries (Norwegian Institute of Wood Technology 2015). By contrast, currently high emission intensive products, such as steel and concrete, are likely to decrease their carbon footprints substantially in the climate change mitigation scenario (The circular economy 2018). In that scenario, the mitigation potential of wood-based products would decrease as well. The end of life energy use of wood-based products would also lead to much lower climate change mitigation potential in the future (The circular economy 2018). Because of this, it is possible that the current studies overestimate the emission reduction potential of wood-based products and energy. On the other hand, if the world is not successful in climate change mitigation, the substitution potential of HWPs remains higher.

Recycling is one fundamental issue that will have an influence on DFs in the future. Cascade uses of wood enables re-use of discarded wood product for another product substitution instead of direct energy use.

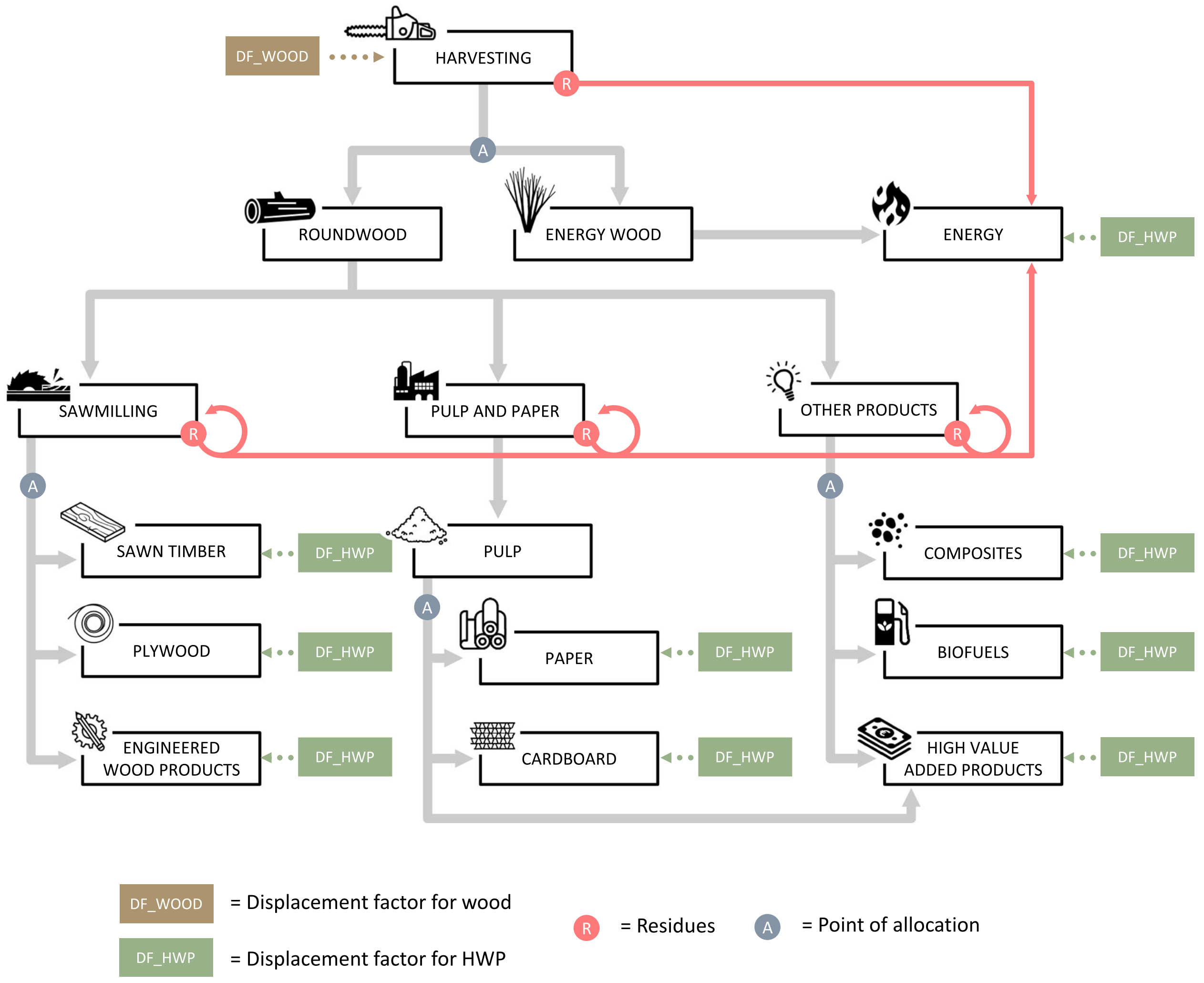

Fig. 4 Connection of wood and residue flows and DFs

Recycling of fossil raw materials also influences wood substitution. For instance, GHG emissions of plastic packaging decreases when raw material recycling increases (The circular economy 2018). As the recycling rate of carton is already higher than for plastic packaging, GHG emission intensities of wood-based packaging cannot decrease to the same extent as those of plastic packaging materials. Thus, substitution effects of replacing plastic packaging with wood-based packaging may decrease in the future.

This review was based on a sample of scientific articles and reports applying DFs. Although we used a structured approach based on a set of keywords to gather the sample of suitable journal articles and reports, it is possible that some relevant studies were not included by a mistake. Another highly influential drawback is that this review focused on studies applying DFs, thus, studied assessing substitution effects of wood use without using a term DF (or substitution factor) were not included. These studies would have provided more insights on the actual substitution effects of wood use, especially for those products and product groups with only few DFs determined (e.g. textiles and packaging products). More extensive studies on the substitution effects of various products are required to provide a more comprehensive understanding on substitution effects of wood use.

Recommendations and conclusions

When applied coherently, DFs are a useful concept to assess substitution effects of wood use. The use of DFs in scientific literature, however, appears to be to some extent arbitrary. More harmonised approaches to develop and apply DFs are needed. To improve the comparability and understanding on DFs, it should be clear which GHG flows are included in DFs. The current trend according to this literature review is to include only fossil GHG emissions. Thus, DFs provide information how much fossil emissions could be avoided in the technosystem with wood use but effects on biogenic carbon flows are not considered. This makes DFs more easily applicable to further studies as dynamic and uncertain changes in forest and HWP carbon stocks are excluded. In the long time-horizon, i.e. centuries, the influence of wood harvesting and use have on forest and HWP carbon stocks may diminish. This is typically not the case in short, i.e. decades, time horizon. Consequently, to provide relevant information on climate change mitigation, DFs should be attached with a consistent consideration of changes in forest and HWP carbon stocks due to wood use studied.

In order to reach appropriate level of mutual understanding within scientific community and between various stakeholders on how to interpret and apply DFs, number of issues need to be discussed and practicalities need to be agreed. We identity the following points crucial when aiming to improve the knowledge, applicability and interpretation of DFs:

DFs can be determined coherently in various ways but the determination should be in line with how and in which context they are applied. In other words, more important than what is included in DFs is along with what information they are applied. We derive the following recommendations on the interpretation of information provided by DFs alone:

- If DFs include all relevant GHG flows including changes wood harvesting and use have on forest and HWP carbon stocks, they describe the overall GHG performance of wood use. It should be noted that then DFs are dynamic and include increasing amount of uncertainties.
- In cases where changes in forest carbon stocks are excluded but changes in HWP carbon stocks are included in DFs, the applicability of them should be limited to study the difference between various end-use applications of wood but *not* the net GHG emissions of wood use.

Abbreviations

DF: Displacement factor; GHG: Greenhouse gas; HWP: Harvested wood product

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Authors' contributions

All authors have contributed to develop the research work. TM, SS and JS designed the literature review. TM, SS and JJ undertook the literature review. JJ and SS designed and finished the figures. TM and SS wrote most of the paper. All authors read and approved the final manuscript.

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Availability of data and materials

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Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing interests

There are no competing interests.

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