Substitution effects of wood-based products in climate change mitigation

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Acknowledgements

The report benefited from the helpful comments from external reviewers, Kim Pingoud, VTT Technical Research Centre of Finland (retired), Sebastian Rüter, Thünen Institute of Wood Research, and Peter Weiss, Environmental Agency Austria. We also gratefully acknowledge the comments from professor Leif Gustavsson, Linnaeus University. We wish to express our thanks for their insights and comments that helped to improve the report, and acknowledge that they are in no way responsible for any remaining errors.

This work and publication has been financed by EFI's Multi-Donor Trust Fund for policy support, which is supported by the Governments of Austria, Czech Republic, Finland, France, Germany, Ireland, Italy, Lithuania, Norway, Spain and Sweden. In addition, authors Leskinen, Hurmekoski and Seppälä also wish to acknowledge financial support from the FORBIO project (no. 14970) funded by the Strategic Research Council at the Academy of Finland.

ISSN 2343-1229 (print)
ISSN 2343-1237 (online)

ISBN 978-952-5980-69-1 (print)
ISBN 978-952-5980-70-7 (online)

Editor in chief: Lauri Hetemäki
Managing editor: Rach Colling
Layout: Grano Oy / Jouni Halonen
Printing: Grano Oy

Recommended citation: Pekka Leskinen, Giuseppe Cardellini, Sara González-García, Elias Hurmekoski, Roger Sathre, Jyri Seppälä, Carolyn Smyth, Tobias Stern and Pieter Johannes Verkerk. 2018. Substitution effects of wood-based products in climate change mitigation. From Science to Policy 7. European Forest Institute.

Contents

Executive summary

Forests have multiple roles, but the role of forests in climate change mitigation has become increasingly important due to the urgent need to reduce climate change impacts.

Forests remove carbon dioxide from the atmosphere via photosynthesis, and store carbon in biomass and soil. When forests are harvested, part of the carbon is released and part is stored in wood-based products. In addition to carbon storage in forest ecosystems and harvested wood products (HWP), **using wood to substitute greenhouse gas intensive-materials and fossil fuels** can have climate benefits.

While the positive role of forests in climate change mitigation is generally well perceived, the contribution of wood products to mitigation is much less known and understood. Current national reporting of greenhouse gas emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and related processes does not attribute the substitution benefits of wood-based products directly to the forest sector. However, this information is important when developing optimal strategies on how forests and the forest sector can contribute to climate change mitigation.

A **substitution factor** (or displacement factor) typically describes how much greenhouse gas emissions would be avoided if a wood-based product is used instead of another product to provide the same function – be it a chemical compound, a construction element, an energy service or a textile fibre. Overall greenhouse gas substitution effects can be estimated by combining information on the quantity of wood products that are produced or consumed, with product-specific substitution factors.

Upscaling to regional or market levels allows us to see impacts from:

- The current consumption of wood products – it shows the level of emissions that would occur if alternative products were used in place of wood.
- An increase in the consumption of wood products with favourable substitution factors – this would contribute to emissions reduction objectives.
- New wood-based products replacing fossil-based ones as part of a future bioeconomy. However, the potential substitution impact is difficult to estimate as commercial scale production processes for many of them do not yet exist.

Due to the potentially high importance of substitution factors in climate change mitigation, the number of available scientific papers linked to substitution has increased in recent years. However, there is a lack of studies that provide an overall synthesis of the topic. At the same time, there is active public discussion about the overall role of the forest sector in climate change mitigation. In this discussion, scientists, experts, decision makers and the media also tend to use somewhat different concepts, definitions and interpretations of the scientific results. As a consequence, the discussion is sometimes confusing or even misleading.

This study aims to help us to better understand what is the most updated knowledge on greenhouse gas effects of various wood products compared to alternative materials, and what are the limitations. We also identify important research gaps that should be covered to have a better understanding of the substitution effects:

- Most studies in the literature focus on construction and significantly less information exists for other product types such as **textiles**.
- Very limited information exists on the associated emissions and potential substitution effects for **biochemicals**, which are considered an important product in the future bioeconomy.
- Most available studies focus on North America and the Nordic countries in Europe, and very few studies consider cases from **Asia, South America, Africa**, or from **south or east Europe**. More studies are needed for better geographical representativeness.

Key messages

- Our review analysed 51 studies, which provided information on 433 separate substitution factors. The large majority of studies indicate that the **use of wood and wood-based products are associated with lower fossil and process-based emissions when compared to non-wood products**. Overall, the 51 reviewed studies **suggest an average substitution effect of 1.2 kg C / kg C**, which means that for each kilogram of C in wood products that substitute non-wood products, there occurs an average emission reduction of approximately 1.2 kg C.

- **The substitution factor is as such important, but does not provide sufficient information to guide policy making**. A more holistic analysis is necessary, which also considers forest and forest soil sinks, harvested wood products carbon storage, permanence of forest sinks and forest disturbances, and potential carbon leakage effects.

- The fundamental aim is not to maximize substitution factors, but to minimize emissions. Tools, means and policies to enhance e.g. recycling and resource efficiency often imply smaller emissions for both wood and non-wood based products. **Resource-efficiency and minimizing material waste should be a simultaneous policy target with climate mitigation.**

- **There is a lack of knowledge on climate impacts of emerging forest products.** The use of wood is expected to increase in the future, for example in textiles, packaging, chemicals, biofuels and a large variety of downstream niche markets. In general, the research literature does not yet capture sufficiently these new and promising areas. Research funding should be targeted to this area e.g. in the EU.

- Climate mitigation is only one major policy target. **When considering the impacts of different materials and products, it is also important to consider all sustainable development goals (SDGs)**, aiming to find synergies between the different goals and policy targets, and minimizing trade-offs.

1. Forests, wood products and climate change mitigation

Forests provide multiple benefits to society, including biodiversity and ecosystem services, such as CO_2 sequestration, forest products, water and recreation. The maintenance and improvement of these functions is an integral part of sustainable forest management (SFM) (FAO, 2010). Forest products supply a range of economic and social benefits, including contributions to the overall economy via income, tax and employment generation. Forest products also provide economic incentives for forest owners to replant, manage and maintain forests against disturbances such as forest fires.

In recent years, the promotion of a bioeconomy based on renewable resources has received much political attention, because it is expected to contribute to climate change mitigation, help to replace non-renewable resources, as well as environmental and energy security (Purkus et al. 2018). Hetemäki et al. (2017) argued for a circular bioeconomy as a new economic paradigm that is necessary to achieve the globally agreed Paris climate agreement and sustainable development goals (SDGs). Following this need there is expected to be increasing demand in the future for renewable and low emission products. However, while the bioeconomy is seen as one pillar for more sustainable production, changing current fossil fuel-based production to a low emission production based on renewable sources is challenging (Siebert et al. 2018). The solution requires structural changes in production and consumption, with businesses and consumers becoming increasingly aware of the environmental impacts of their behaviour.

Forests have multiple roles, but the role of forests in **climate change mitigation** has become increasingly important due to the urgent need to reduce climate change impacts. Forests remove carbon dioxide from the atmosphere via photosynthesis, and store carbon in biomass and soil. When forests are harvested, part of the carbon is released and part is stored in wood-based products. In addition to carbon storage in forest ecosystems and harvested wood products (HWP), using wood to substitute more greenhouse gas (GHG) intensive materials and fossil fuels can have climate benefits by reducing fossil GHG emissions from other sectors. While the positive role of forests in climate change mitigation is generally well perceived, the **contribution of wood products to mitigation is much less known and understood** by the general public (Ranacher et al. 2017).

Overall GHG substitution effects can be estimated by combining information on the quantity of wood products that are produced or consumed with product-specific substitution factors. A **substitution factor** (or displacement factor) typically describes how much GHG emissions would be avoided if a wood-based product is used instead of another product to provide the same function - be it a chemical compound, a construction element, an energy service or a textile fibre. In the literature, the terms substitution factor and displacement factor are often used interchangeably, but in this study we use substitution factor (SF).

Current national reporting of GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and related processes is based on emissions from five major emission sectors: energy; industrial processes and product use; agriculture; land use, land-use change and forestry; and waste. This sector-based reporting accounts for GHG substitution effects through reduced emissions from, for example, the energy or industry sectors, but it does not attribute these substitution benefits of wood-based products directly to the forest sector. However, this information is important when developing optimal strategies on how forests and the forest sector can contribute to climate change mitigation.

Existing studies (e.g. Sathre & O'Connor 2010) suggest that substitution can provide significant climate mitigation benefits through the substitution of products with higher GHG life cycle emissions. Yet the quantification of these substitution benefits is not straightforward and involves many uncertainties. For example, substitution effects depend on the type of wood product being considered, the type of non-wood product that it substitutes, the different operating life as well as the end-of-life management of wood and non-wood products, and the use of harvest and processing residues. Analyses are also complicated by the use of integrated wood production systems that produce multiple products and the interdependencies between these. For example, the sawmilling industry produces wood for construction materials and sawmilling residues serve as raw material for energy and paper products. Estimating future substitution benefits is challenging because new production technologies, product developments and the development of bioeconomy markets are likely to change the GHG emissions.

Due to the potentially high importance of substitution factors in climate change mitigation, the complexity and uncertainties in estimating such factors, and rapidly emerging new wood-based products in areas such as textiles and plastics, the number of available scientific papers linked to substitution has increased in recent years. However, **there is a lack of studies that provide an overall synthesis of the topic**. A much cited review study was published almost a decade ago (Sathre & O'Connor 2010) so there is clearly a need to update our knowledge. At the same time, there is active public discussion about the overall role of the forest sector in climate change mitigation. In this discussion, scientists, experts, decision makers and the media also tend to use somewhat different concepts, definitions and interpretations of the scientific results. As a consequence, the discussion is sometimes confusing or even misleading. We need to better understand what are the most updated GHG effects of various wood products compared to alternative materials and what are the limitations.

This study seeks to fill the gaps in knowledge, and reviews the current understanding of GHG substitution effects from the use of wood-based products. Specifically, it looks at the following questions:

- How can the GHG substitution factors of wood products be defined and assessed?
- What are the magnitudes of the GHG substitution effects of wood-based products?
- What are the key sources of variability and uncertainty, which affect the GHG substitution effects of wood-based products?
- What are the wood products or product groups that generally show the highest potential in terms of avoided emissions?
- How can substitution factors from the product level be upscaled to the market level?
- What is the scale of overall substitution benefits for wood-based product markets, and how can these substitution benefits be realized?
- How should we interpret substitution factors in climate change mitigation, and apply them in decision making and policy planning?

2. Mitigation effects of wood products

2.1 What are substitution factors and how can they be assessed?

A starting point

The potential of forests and wood biomass to mitigate climate change by reducing greenhouse gas (GHG) emissions is widely recognized, but challenging to quantify. Capturing the mitigation benefits through the use of forest products requires information on carbon storage in forest ecosystems and wood products, as well as substitution benefits where emissions are avoided by using wood products instead of other fossil-intensive products or fossil energy. Thus, we need a way to quantify the difference between the GHG emissions resulting from the use of wood and a predominantly non-wood alternative, relative to the amounts of wood used in the wood product and non-wood product. The measure used for this quantification is called the substitution factor (or displacement factor).

Substitution factors are used to assess the **substitution impact** of wood-based products by multiplying product volumes by their corresponding substitution factors. However, the substitution impact (i.e. avoided fossil GHG emissions) is only one component in climate change mitigation and the GHG emission balance related to wood use. In order to estimate the overall climate impact, one should also consider carbon stock changes in trees and soil, and harvested wood products sink (HWPs) over time. The assessment of the biogenic carbon balance in forests can be made with the help of forest simulation models.

Computing the substitution factor

The SF can be formally expressed as an equation (Sathre & O'Connor 2010).

Equation 1

$$\mathrm{SF} = \frac{GHG_{non\text{-}wood} - GHG_{wood}}{WU_{wood} - WU_{non\text{-}wood}}$$

$GHG_{non\text{-}wood}$ and GHG_{wood} are the GHG emissions resulting from the use of non-wood and wood alternatives.

WU_{wood} and $WU_{non\text{-}wood}$ are the amounts of wood used in wood and non-wood alternatives.

A SF is a unitless ratio, when the GHG emissions are expressed in mass units of C, and the wood use is expressed in mass units of C contained in the wood.

If the value of the equation is positive, this indicates that using a wood product causes less GHG emissions than using the non-wood product (assuming, as is typically the case, that the wood product contains more wood than the non-wood product).

There are two approaches to calculate the wood used (WU) in the denominator. In one approach, WU includes only the wood contained in the end-use products. In the second approach, WU includes all the harvested wood (including forest and wood processing residues) used for producing a wood end-product. Both approaches are acceptable, but they lead to different overall calculation rules in the assessment of substitution impacts.

A SF should ultimately consider all significant fossil GHG emissions to the atmosphere from the wood and non-wood product systems. This should include emissions from raw material extraction, processing, transportation, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal. In case not all processing stages are considered, the system boundaries need to clearly define what emissions are included in the substitution factors and what has been disregarded.

Net CO_2 emission is typically the most important emission for climate effects, while emissions of other GHGs (e.g. methane emissions from landfilling, nitrous oxide from fossil fuels used in transport) can also have a significant influence. By using the concept of global warming potential (GWP), the different GHG emissions can be converted to a commensurable unit, expressed as CO_2 equivalents of the different gases for a given timeframe (typically 100 years).

Standards are increasingly formulated or improved to guide life cycle assessments. The global standards 14040 and 14044 by the International Organization for Standardization (ISO) are key in this respect; they specify the overall requirements and provide guidelines for life cycle assessments. For some sectors – especially the construction sector – additional standards exist; for example, ISO standard 21930 provides methodological guidelines on how to assess the environmental impact of buildings and civil engineering work, along their entire life cycle. In addition to these global standards, related standards are being developed that are regionally relevant (for example, the European standard EN 15804 on the sustainability of construction works).

The comparison of life cycle GHG emissions for a product requires that a wood product and a non-wood product have the same functionality, and that the products have the same functional unit (ISO 14040 and 14044). The functional unit provides a reference to which the inputs (raw materials and land use) and outputs (emissions) are calculated. The calculations of GHG emissions are based on the rules of life cycle assessment (LCA) (ISO 14040 and 14044). The result of the SF depends on the quality of input data and assumptions used in the LCA (see section 2.3).

Components of a substitution factor

SFs include the effects of different life cycle stages of products. Figure 1 shows system-wide integrated material flows of wood products. Fossil GHG emissions related to those material flows should be taken into account in the determination of SFs. These GHG emissions will occur at different points in time during the life cycle.

To increase the transparency of the calculations, and to facilitate comparison of the avoided net fossil GHG emissions of wood utilization between different life cycle stages, different components should be included in the assessment of SFs:

- $SF_{production}$ is the difference in fossil GHG emissions during the production stages of wood-based products and functionally equivalent non-wood products. $SF_{production}$ includes the fossil GHG emissions allocated to an end-product caused by forestry and harvesting practices, mining and processing of minerals and metals, transportation of raw materials, product manufacturing, and transportation to customers. Forest residues and wood processing residues used for energy for end-products should be taken into account in the determination of $SF_{production}$.
- SF_{use} is the difference in fossil GHG emissions during the re-use and maintenance stages of wood and non-wood end-products.
- $SF_{cascading}$ includes the GHG effects of recovery of materials from end-of-life products.
- $SF_{end\text{-}of\text{-}life}$ is the difference in fossil GHG emissions during the end-of-life management stages of wood and non-wood products.

The substitution factor is dynamic, not static. Thus, in the future, the emissions of different life cycle stages from raw material extraction to the factory gate caused by wood and non-wood alternatives may change, which could also change the $SF_{production}$ values of wood products. In addition, in a future circular economy efforts to reuse and recycle will increase the lifespans of different raw materials. Most wood products at the end of their service life will be combusted with or without energy recovery, or will be placed in landfill, and these effects are included in $SF_{end\text{-}of\text{-}life}$. However, the EU directive on

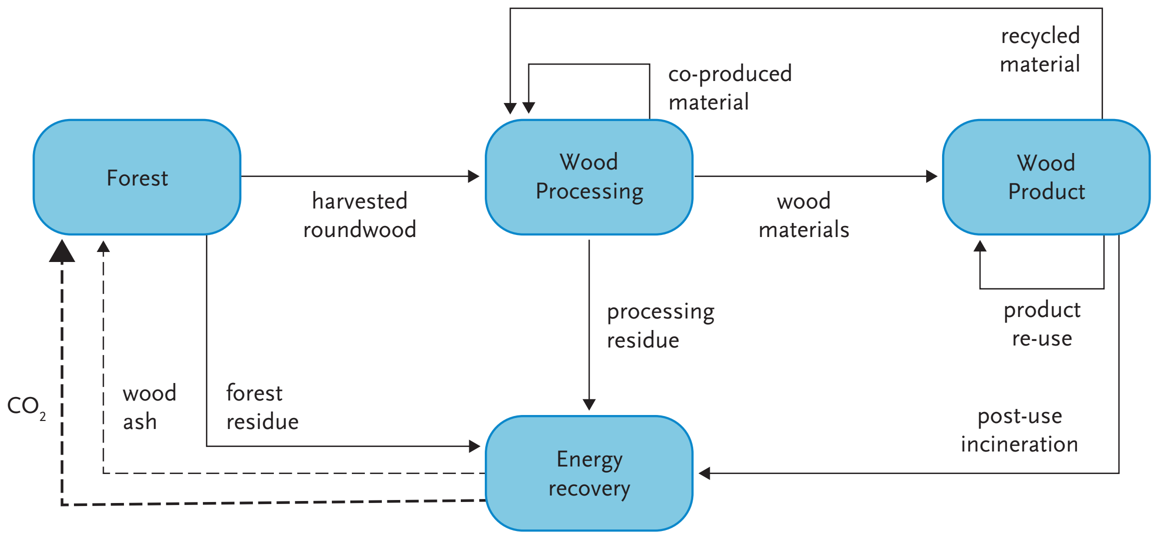

Figure 1: System-wide integrated material flows of wood products (Dodoo et al. 2014) causing GHG emissions. These should be taken into account in the calculation of SFs. In addition, specific material flows related to non-wood products with similar functionality and their GHG emissions should be assessed.

landfilling of waste requires that landfilling should not be a future option.

2.2 What do we know about substitution effects by wood-based products?

Literature review

Numerous studies have been published to date that have estimated substitution factors for wood and wood-based products. Existing reviews (e.g. Petersen & Solberg 2005; Werner & Richter 2007; Sathre & O'Connor 2010) focused mostly on the construction sector and generally found that SFs critically depend on the type of wood product, the type of non-wood material that is replaced and the post-consumer treatment of the wood.

To improve the understanding of the substitution effects of all wood and wood-based products, we conducted a systematic review of studies published before April 2018. The review included only studies that provided original substitution factors, or studies that contained emission data for a wood product and a functionally equivalent non-wood product that could be used to calculate substitution factors. Studies that relied on substitution factors from previous studies were excluded from the review, unless they provided new information by e.g. expanding the system boundaries of the previous studies. In total, the review focused on 51 individual studies (see the online materials).

Most of the studies reviewed focused on North America and the Nordic countries in Europe (i.e. Finland, Sweden, and Norway). Very few studies focused on Asia or South America and no study focused on Africa. Very few studies focused on south or east Europe. All studies provided information on the production stage of the product life cycle. Seventeen studies focused only on the production stage, while all other studies included two or three life cycle stages, but no study included four stages.

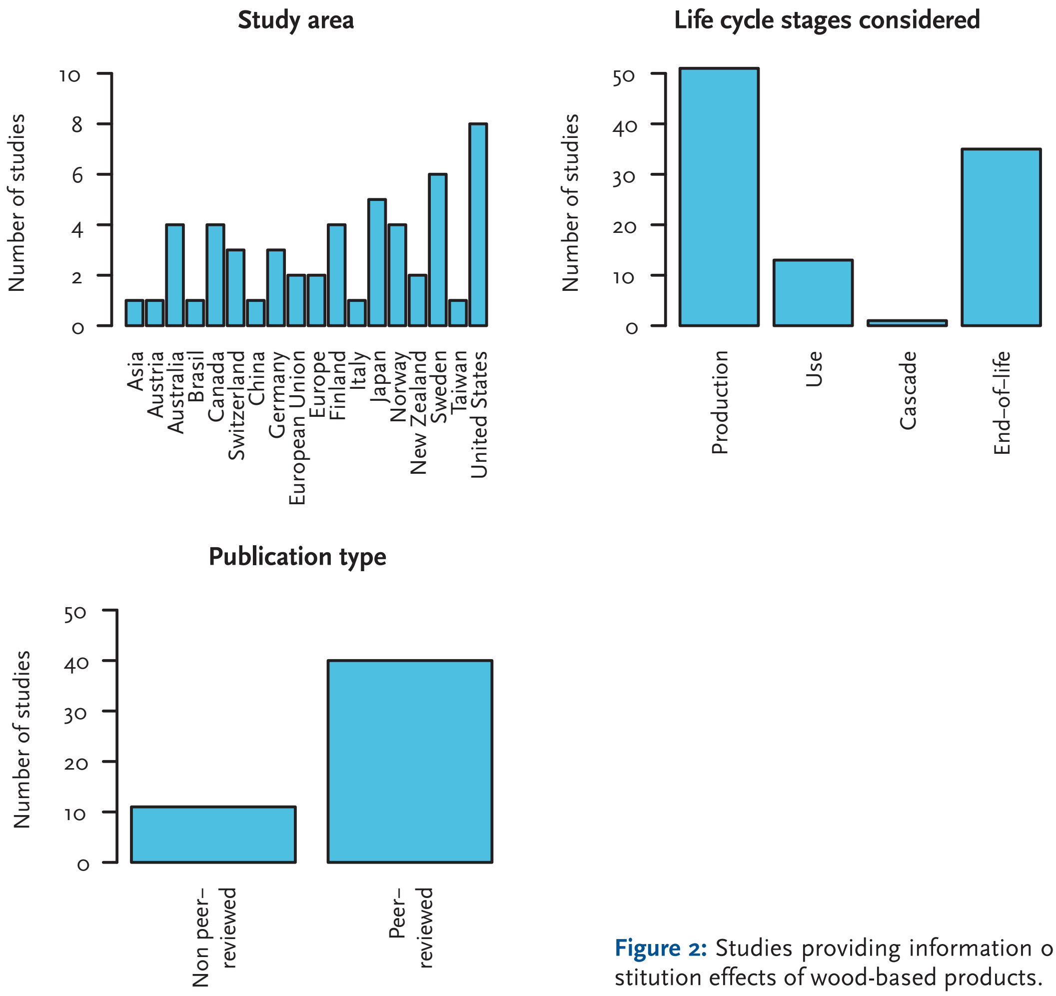

Figure 2: Studies providing information on the substitution effects of wood-based products.

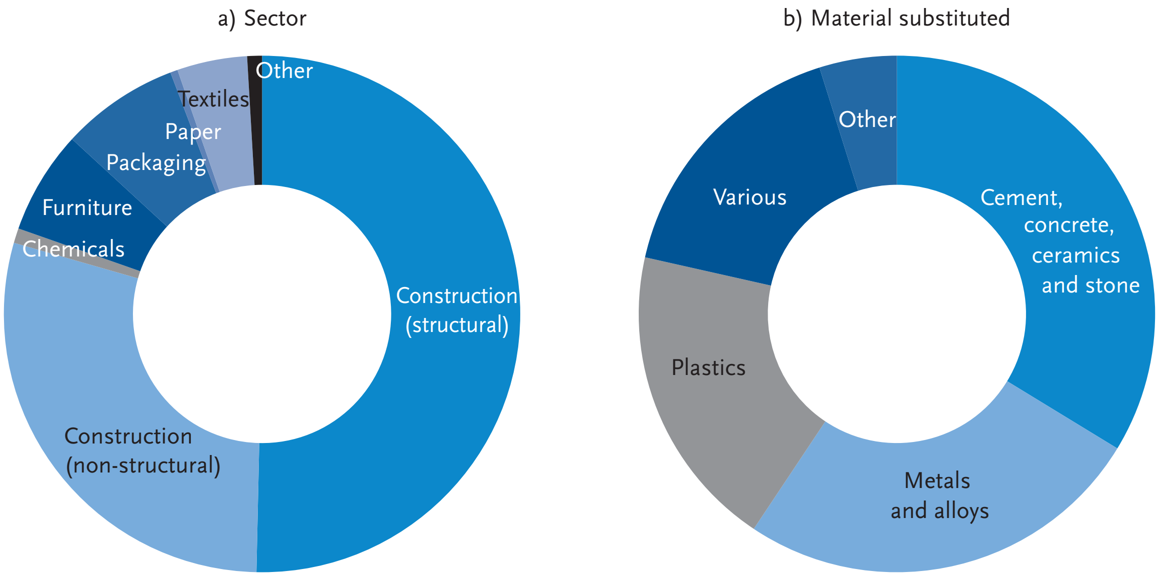

Figure 3: Summary of information available for substitution factors for (a) different sectors, and (b) non-wood materials being substituted.

In addition, very few studies provided information on the substitution effects of the product use and cascading stages. The majority of studies (78%) have been published in peer-reviewed literature. However, due to the large amount of substitution factors derived from a few non-peer reviewed studies (e.g. Rüter et al. 2016; Valada et al. 2016), only 45% of the substitution factors are from peer-reviewed literature.

Overall substitution effects derived from the literature

The 51 studies that were reviewed provided information on 433 separate substitution factors. Most of the substitution factors (79%) related to the construction sector and substantially fewer substitution factors were available for other product types (i.e. furniture, packaging, and textiles) and especially for paper and chemicals (Figure 3a). Approximately one-third of the substitution factors was for wood substituting for cement, concrete, ceramics or stone. A quarter of all the factors was for wood substituting for metals and alloys, mostly steel and aluminum (Figure 3b). Approximately 20% of the factors related to plastics, for example polyethylene, polypropylene, polystyrene and polyvinyl chloride. Some factors did not relate to one specific non-wood material being replaced by wood, but to various materials instead (e.g. a range of materials used to construct a building). Finally, approximately 5% of the substitution factors related to wood substituting other materials such as glass, rock wool, asphalt, cotton, etc.

To enable comparison of the substitution factors, we applied Equation 1 and expressed the values in a common unit of mass of C in the final wood product. We did this by calculating the GHG emission reduction due to using a wood product (expressed in mass units of carbon) per unit of additional wood used in the wood product compared to the non-wood product (expressed in mass units of carbon). Where necessary for unit conversions, we used IPCC default values and assumed an air-dry moisture content of 15%. Carbon impacts in forest ecosystems (biomass, soil) were excluded from the calculated substitution factors.

Overall, **the 51 reviewed studies suggest an average substitution effect of 1.2 kg C / kg C**, which means that for each kilogram of C in wood products that substitute non-wood products, there occurs an average emission reduction of approximately 1.2 kg C. However, this overall substitution factor is subject to large variability, as 95% of the values range between -0.7 and 5.1 kg C / kg C. An important reason for this is that these values are based on many different product types, non-wood materials that are substituted, production technologies, number of life cycle stages considered, and end-of-life management practices. However, **over 90% of the substitution factors that include two or more life cycle stages have a value greater than zero**. This implies that the use of wood products from a sustainably managed forest in the long-term generally provides GHG climate benefits over functionally equivalent products made from other materials.

Substitution effects of life cycle stages

Various studies provided information on the substitution effects during the life cycle stages of a product (i.e. production, use, cascading and end-of-life; see Figure 2). The substitution benefits from using wood over alternative non-wood products are largely gained from reduced fossil GHG emissions during the production stage of the wood product. The average of all reported substitution factors for the production stage was 0.8 kg C / kg C wood product. In addition, substantial substitution benefits are also often obtained from energy recovery at the end-of-life stage; the average of all reported substitution factors for this life cycle stage was 0.4 kg C / kg C wood product. Most studies did not quantify emissions during the product use stage and often assumed these emissions to be equal for the wood product and its non-wood equivalent. The very few studies that did report on emissions from the product use stage suggest that emissions of wood product use are slightly higher when compared to non-wood products. The average of all reported substitution factors was -0.05 kg C / kg C wood product, as they assumed that wood products require more maintenance. Few studies considered the cascading stage, but the information available from the literature suggests that cascaded use of wood provides minor climate benefits. The average of all reported substitution factors with regards to cascading was 0.01 kg C / kg C wood product.

While substitution factors are expressed per unit of C in final wood products, there are numerous associated flows of biomass by-products such as harvest and processing residues. Modern wood processing industries commonly use sawmill residues as an energy source, which contributes – through avoided fossil emissions – to the production stage substitution benefits of wood products. Several studies have assessed the climate benefits of utilizing biomass residues from timber harvest, finding that using harvest residues for bioenergy increases SFs by about 0.4 - 0.8 kg C / kg C, depending on the fossil fuel replaced (Gustavsson & Sathre 2006; Eriksson et al. 2007). Stump harvesting can provide an additional substitution benefit of 0.2 - 0.5 kg C / kg C.

The substitution benefits from the end-of-life stage (0.4 kg C / kg C wood product) are primarily due to energy recovery from post-use wood materials instead of fossil fuels. Based on information provided in the reviewed studies, benefits are higher (up to 1 kg C / kg C) when recovered wood is used to substitute carbon-intensive coal, and lower when it substitutes gas or oil. Several studies considered landfilling as the end-of-life for wood products, which generally reduced the substitution benefits due to both the formation of methane in landfills and the reduction in fossil fuel substitution by recovered woody biomass, but also introduced high variability. In addition to the substantial uncertainties regarding biophysical landfill processes, there is also a diversity of assumptions used in the studies, leading to contradictory conclusions of landfill effectiveness. In contrast, energy recovery from post-use wood is found to provide reliable climate benefits relative to fossil fuel burning.

Construction sector

Many studies report that the use of wood for construction purposes results in climate benefits when compared to non-wood products. Substitution factors are generally available for structural (e.g. a building, internal or external wall, wood frame, beam) and non-structural (e.g. a window, door, ceiling cover or floor cover, cladding, civil engineering) construction products. The substitution factors derived from the literature showed substantial variability; the average SF for structural construction was 1.3 kg C / kg C wood product, with 95% of the values ranging between -0.9 and +5.5 kg C / kg C wood product. Similarly, the average SF for non-structural construction was 1.6 kg C / kg C wood product, with 95% of the values ranging between +0.2 and +4.7 kg C / kg C wood product.

The large variability in these estimates can be explained by differences in assumptions, data and methods. In general, substitution factors are often estimated for a particular wood product and compared to a certain functionally equivalent, non-wood alternative and it is not straightforward to generalize the results from such comparisons. However, using wood or wood-based products in many cases results in lower emissions during the production stage, compared to most other products. At the end-of-life stage, wood-based products can be easily used for energy production, while metals and alloys can be recycled,

Table 1. Summary of the average substitution factors by broad product categories. The reported averages included are based on studies considering at least two life cycle stages. Note that there is large variability around the averages, and some of these numbers are based on only one or few studies. Therefore, these numbers cannot be generalized and should be interpreted with care.

Product categories	Average substitution effects kg C / kg C wood product
Structural construction *(eg building, internal or external wall, wood frame, beam)*	1.3
Non-structural construction (*eg window, door, ceiling and floor cover, cladding, civil engineering)*	1.6
Textiles	2.8
Other product categories *(e.g. chemicals, furniture, packaging)*	1 – 1.5
Average across all product categories	**1.2**

giving smaller end-of-life stage substitution benefits for wood products. In contrast, cement, concrete, ceramics and stone have limited end-of-life utility, leading to higher substitution factors for wood products.

Textiles

Based on the existing literature, using wood for producing textiles may to lead to a substitution effect of 2.8 kg C / kg C, thereby providing the largest substitution benefits across all product types considered. The two existing studies (Rüter et al 2016; Shen et al. 2010) report that the production of wood-based fibres such as viscose, lyocell and modal results in lower levels of CO_2 emissions than the production of cotton or synthetic fibres. The production technology and resource base that is used could have a significant effect on the estimated substitution effects. For example, an integrated textile fibre and pulp plant using modern technology and factory biomass for process energy was found to give lower levels of GHG emissions compared to conventional textile production technology using market pulp instead of integrated own pulp (Shen et al. 2010).

Other products

Other product categories, such as wood-based chemicals, packaging and furniture, generally result in moderate substitution benefits with average factors ranging between 1 and 1.5 kg C / kg C wood product. However, these results are based on only a few studies and are limited to a few product comparisons only. For example, only one study (Rüter et al. 2016) reported on substitution effects related to a chemical product by comparing adhesives made from lignin with adhesives made from phenol. Obviously, findings from a single comparison for a specific product cannot be generalized to other chemical products. Similarly, only one study exists that compares the life cycle emissions of a printed magazine and an electronic tablet version. The study highlights that the substitution factor may be a positive or negative value, strongly depending on the number of readers for the tablet edition, number of readers per copy for the print edition, file size, and degree of use of the tablet for other purposes (Achachlouei & Moberg 2015).

2.3 Variability and uncertainties of substitution factors

Estimating the substitution benefits of wood products is a challenging task, and many factors contribute to the variation of the SFs results. For example, there is large variability in the SFs obtained for wood-use in construction and the SF estimates contain a certain degree of uncertainty. *Variability* is due to the inherent heterogeneity of the wood and non-wood products considered, the production technologies used, as well as the methodological differences between the studies. This variability cannot be reduced, but can only be characterized. *Uncertainty* refers to the degree of precision with which the SFs are estimated, and it can be reduced by generating and collecting more and better data.

Methodological choices can greatly affect the estimated SFs. For example, system boundary definitions (Rivela et al. 2006; Werner et al. 2007), temporal boundaries (Demertzi et al. 2017; Edwards & Trancik 2014) and the choice of allocation method when dealing with multi-functionality (Cherubini et al. 2011; Jungmeier et al. 2002; Sandin et al. 2015; Taylor et al. 2017) can greatly affect the estimated SFs and their variability. A difficulty encountered in the meta-analysis is the lack of detailed information on how the emissions from wood products and their substitutes are modelled. Often crucial information like the allocation procedure used is missing and, in several cases, the studies are not transparent concerning the assumptions made.

A source of variability is the inconsistency between studies in terms of GHG considered and how they are accounted for. Most of the studies consider only the fossil CO_2 emissions and, in some cases, other GHGs, e.g. methane and nitrous oxide. Usually, the biogenic CO_2 exchanges are not included in the SFs and they are either ignored or taken into account by separate calculations and/or assumptions.

One additional reason for increased variability of the estimated SFs is the difference between the types of energy production systems in different countries and regions. For example, the estimated substitution effect can substantially change based on the assumed type of energy to be replaced (Gustavsson & Sathre 2006; Cherubini et al. 2009; Cherubini & Strømman 2011).

While the meta-analysis of SFs attempted as much as possible to differentiate by life cycle stage components, also within each stage the assumptions used in the studies can contribute to variation in the results. A prominent example is the end-of-life phase, where the assumption on the final fate of wood (e.g. landfilling vs. incineration) and the methodological approach used to account for it (e.g. allocation vs. system expansion) increases the variability of the results (Cherubini & Strømman 2011; Sandin et al. 2015; Werner et al. 2007).

In addition, the reviewed studies are essentially based on current product design, technologies and energy supply. While the past and current situation is well known, future product design and changes in technologies and energy supply are difficult to predict and depend on many factors including future policy instruments. It is thus challenging to estimate how these future changes will impact substitution benefits. All these aspects contribute to the uncertainty in the substitution factors.

Cascading is seen as a way to better use resources and contribute to climate change mitigation. The results of our review indicate that the direct climate benefits due to cascading use of wood are marginal when compared to the other life cycle stages. Nevertheless, the issue has been addressed in only one study (Rüter et al. 2016), and to fully understand the climate mitigation potential of wood product cascading further studies are needed.

Both wood and non-wood production can have important geographical differences in terms of technological efficiency and energy production systems. The reviewed studies are geographically restricted to mostly industrialized countries, in particular North America and Nordic European countries, which are areas that generally have a high technological development level. Many other areas of the world are little or not covered at all, despite their relative importance in the global wood markets (UNECE 2018). Thus, the results here are not likely to be globally representative. In addition, most of the studies assume domestic production of roundwood, while this is not always the case due to the international trade of wood (Bais et al. 2015).

While in the meta-analysis we included studies as coherently as possible, there are unavoidable differences which contribute to increased uncertainty and variability, reduce the representativeness of the results, and make their interpretation more difficult. The variation in the results could be reduced by improving the quantity and quality of data available in the future, and by following a harmonized, agreed-upon methodology to derive the SFs. Reflecting this, in recent years a number of international standards have been developed to assess the sustainability of wood in the construction sector, and these harmonization efforts are still ongoing (Passer et al. 2015). These standards aim to provide methodological guidelines on how to assess the environmental impact of building products along their entire life cycle. The adherence to these standards in the future will undoubtedly facilitate a more systematic comparison of the environmental performance of wood products.

Last but not least, it must be stressed that while calculating the SF provides information on the climate benefits of the products, it does not deliver information on how efficiently the wood resource is used, i.e. it does not tell us the amount of raw wood necessary to produce the product. This efficiency of the wood processing along the production chain is also an important aspect that should be considered.

3. Substitution impacts on regional and market levels

Chapter 2 compared the GHG emissions of wood-based products with alternative products that provide the same function. The resulting technical concept, a substitution factor, can be upscaled to estimate the substitution impacts at a regional or market level. In this section, we highlight factors that should be considered in a full analysis of market-level GHG substitution impacts, and introduce markets where significant gains from product substitution could be expected, on account of the increasing use of wood in major global markets.

Using the substitution factor for wood products to upscale the GHG benefits to regional or market levels provides at least three relevant perspectives:

- The *current consumption* of wood products indicates the level of emissions that would occur if alternative products were used in place of wood.
- An *increase in the consumption* of wood products with favourable substitution factors would contribute to emission reduction objectives.
- *New wood-based products* replacing fossil-based ones as a part of a future bioeconomy. In contrast to the first two perspectives, the potential substitution impact of emerging products remains highly speculative, as the commercial scale production processes for many of them do not yet exist, or substitution studies have not yet been carried out.

Current consumption

Industrial roundwood production was 355 million m^3 in the EU in 2016 (FAOSTAT). This is mainly used by traditional forest industries, which consist of solid wood products industries, pulp and paper industries, and their downstream manufacturers (Figure 4). Some of the most important uses of wood relate to communication papers, construction, packaging, fuels, and emerging uses for textiles and chemicals.

The consumption of forest products has traditionally been primarily driven by population, income, and prices, and is heavily influenced by policies, institutions and culture (Toppinen & Kuuluvainen 2010). However, recently the consumption of emerging products, such as cross-laminated timber (CLT) solid wood products and dissolving pulp, has increased rapidly, which traditional demand factors fail to explain (Hetemäki & Hurmekoski 2016).

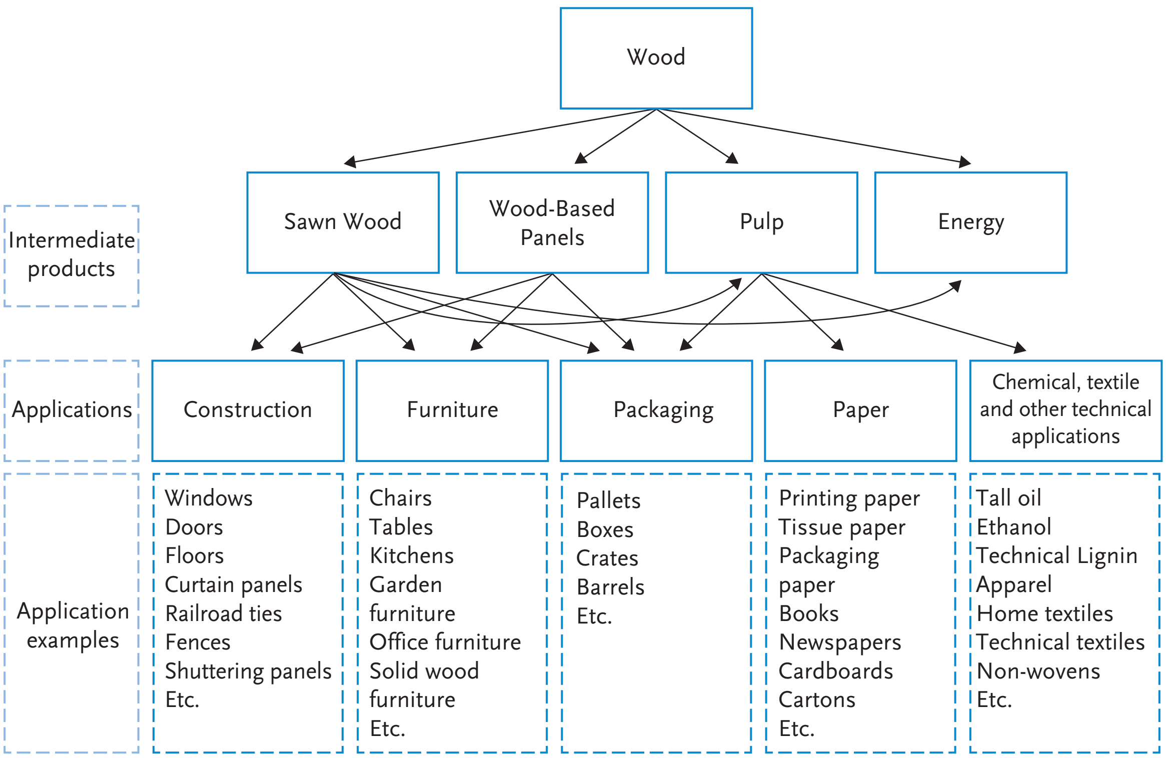

Figure 4: Most typical wood utilization paths.

Income and prices predominantly determine short-term business cycles. However, structural drivers such as technological change, environmental considerations and changes in consumer preferences typically cause changes on a timescale of decades, although the recent developments in CLT and dissolving pulp indicate that this can take place also in the short-term.

On a global level, the consumption of most forest products is generally expected to grow along with the population and GDP growth. In the EU, the consumption growth of many forest products - in the absence of major policy changes - is expected to remain modest for the next decade (Figure 5), due to an ageing population, assumed sluggish economic growth and increasing global competition.

3.1 Upscaling product-level GHG benefits to regions or markets

The substitution factors reviewed in Chapter 2 are based on comparing two specific products that provide interchangeable values and services. To analyze substitution at the market level, it is necessary to compare the overall mix of forest products to a mix of competing products, and to multiply the respective volumes of the products by the substitution factors (e.g. Knauf, 2016; Soimakallio et al. 2016; Braun et al. 2016a; Suter et al. 2017; Smyth et al. 2017).

Considering that the SF ought to be associated with very specific substitution processes for each and every end use of wood, the unavailability of statistical data necessitates making a number of approximations and assumptions, which may lead e.g. to overestimation of substitution impacts. Importantly, it makes a difference whether the upscaling refers to the amount of wood contained in the final product, or the amount of wood harvested to produce the given product. Both of these approaches can be valid, but here we apply only the former approach.

Figure 6 summarizes the production for some of the most important forest products in the EU and their respective substitution factors. Overall, sawnwood—around 50% of which is used for construction—would seem to create the largest substitution benefits because of the large market volume and relatively large substitution factor. This is consistent with results from earlier literature (e.g. Kayo et al. 2015; Braun et al. 2016b).

Due to their large volume, printing and writing paper as well as packaging paper could have a

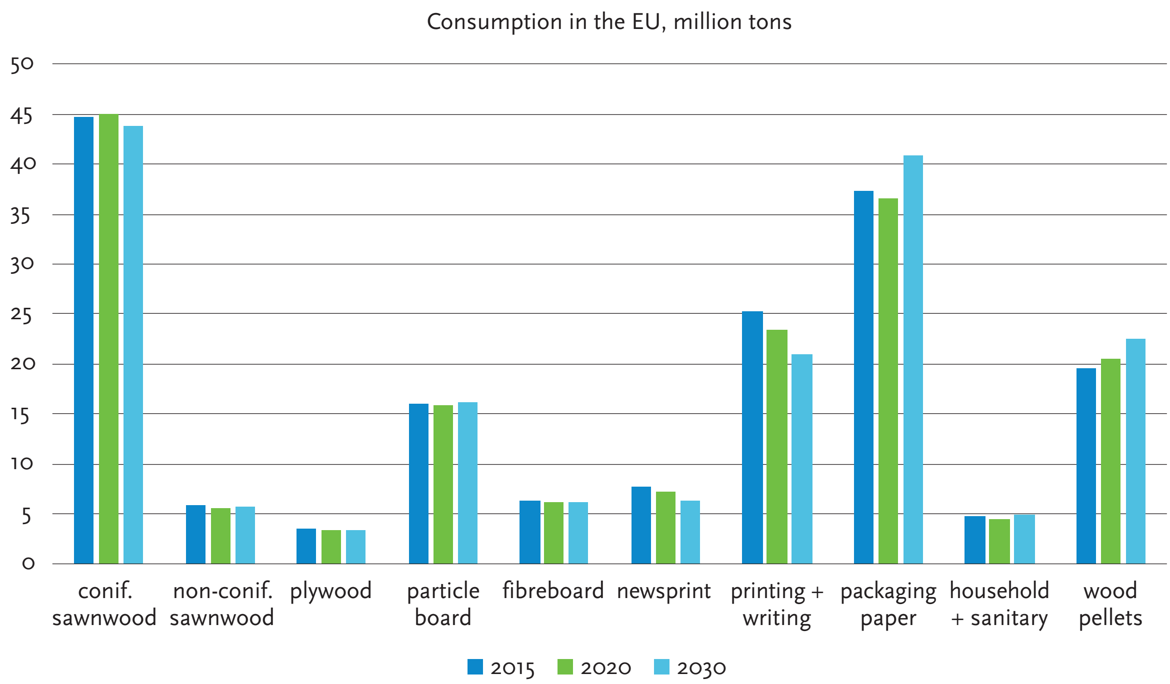

Figure 5: Development of traditional products wood consumption within the EU until 2030 based on data published in Jonsson et al. (2018). Total industrial roundwood harvest production for the EU in 2016 was approximately 355 Mm^3, and 1900 Mm^3 globally (FAO).

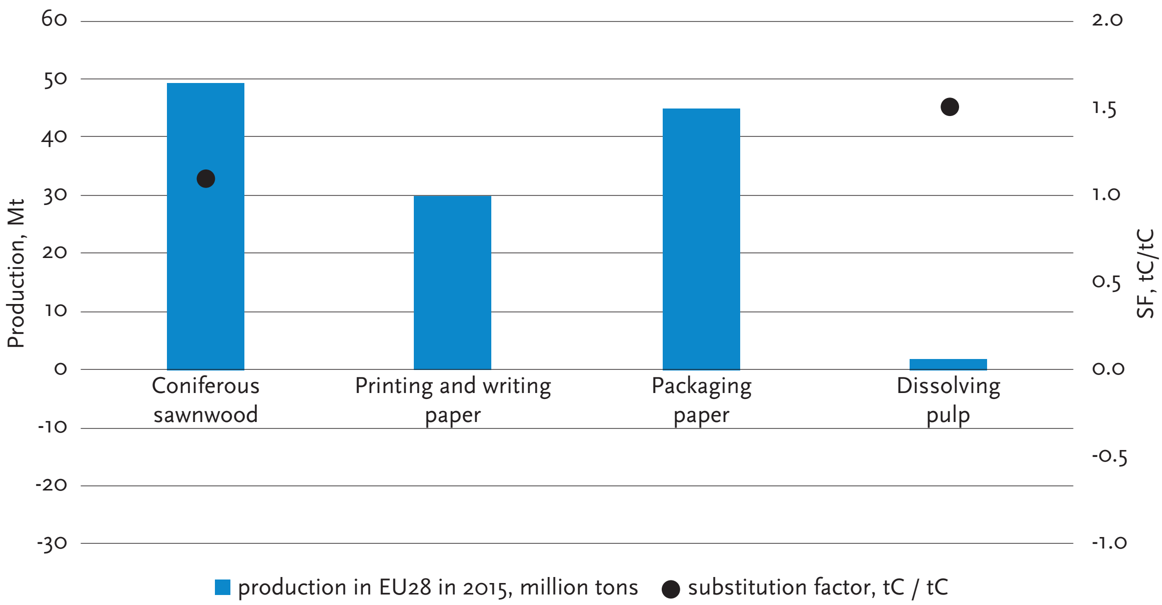

Figure 6: Annual production volume (bars) of selected forest products in the EU28 in 2015 and respective weighted substitution factors (dots). Substitution factors were weighted by end uses for coniferous sawnwood and dissolving pulp (cf. Table 2). Substitution factors for paper categories are not shown – there were insufficient data available for these categories.

significant impact on the overall substitution impact of industrial wood usage, yet there is insufficient information available on substitution factors to assess the substitution impact of these product categories. Graphic papers (printing and writing papers and newsprint) are increasingly being substituted by electronic media, yet there is currently only one study quantifying the substitution impact. The possible substitution impact of packaging paper is even less known due to the variety of alternative materials. For example, from environmental perspectives (not only climate mitigation) some of the most promising substitution possibilities seem to be in replacing plastic packages with wood fibre-based packages (Hurmekoski et al. 2018).

The body of literature providing a weighted substitution factor is fairly small, and it mostly focuses on solid wood products and energy. On a regional level, two recent comprehensive studies report weighted SF of around 0.5 tC / tC for the production stage (Suter et al. 2017; Smyth et al. 2017). However, several precautions are required when interpreting a regional SF. Information on wood product production is generally available, but it is often difficult to determine the exact end uses of wood, and the alternate non-wood product that could have been used. Intermediate products such as sawnwood and panels can be used to make a wide range of final products with potentially very different substitution factors, and this makes it difficult to weight the substitution factors by the volume of each end use product. Previous studies have compensated for missing information by making assumptions, modelling specific processes, or using statistical databases (see online materials).

3.2 Market level substitution benefits

Here, we look at the marginal changes caused by increased market share of wood products in selected global markets, and the consequent additional climate benefits when compared to the current state. The marginal increase can be influenced by, for example, innovation (technology push), policy (regulatory push) or changes in relative prices or consumer preferences (market pull), or a combination of several or all of these.

We present three illustrative case studies that provide quantitative estimates of avoided emissions in the construction and textiles markets. Table 2 summarizes the main assumption and outcomes of the cases.

Table 2. Market level substitution benefits for three illustrative cases.

Product / functional unit	Sawnwood	Multi-storey wood buildings	Dissolving pulp
Market assumption	Production of sawnwood increases at an annual rate of 1.8% to 2030 (Hildebrandt et al. 2017)	Wood products gain a 1% increase in the annually built floor area of multi-storey residential buildings by 2030	The production of dissolving pulp grows at an annual rate of 3.9% to 2030 (Pöyry 2015)
Substitution case	Around 50% of coniferous sawnwood substituting steel (40%), concrete (40%), and masonry and other (20%) in construction, and around 50% used e.g. in packaging, joinery and carpentry and furniture, substituting various materials	Coniferous sawnwood (50%) and engineered wood products (50%) substituting steel (40%), concrete (40%), and masonry and other (20%) in residential multi-storey construction	Viscose (50%) and Lyocell (50%) replacing polyolefins (75%) and cotton (25%) in apparel
Weighted substitution factor (production stage)	1.11 tC / tC	1.39 tC / tC	1.52 tC / tC
Substitution impact (production stage)	88.7 Mt CO_2eq	4.4 Mt CO_2eq	11.3 Mt CO_2eq
Additional roundwood demand (for the specified end use)	174.8 Mm^3	8.4 Mm^3	31.0 Mm^3

Construction

The construction sector is one of the largest users of natural resources and energy. Data on the market share of wood construction is scattered, but it can be assumed to be below 10% globally, although with significant regional variation (Hildebrandt et al. 2017). It is well known that the construction sector is characterized by regional differences in local building practices created from differences in building cultures, regulations and infrastructures (Hurmekoski 2016). The sector is highly culture-dependent, with significant institutional and technological lock-in in local building practices.

Research literature suggests that despite the inertia in institutional and technological building practices associated with the construction sector, the market share of wood in construction could be gradually increasing (Phelps, 1970; Solberg & Baudin, 1992; FAO 2016). Over the past decade, cross-laminated timber and laminated veneer lumber markets in particular have grown rapidly (Espinoza et al. 2015). The main comparative advantage of wood in construction can be argued to be the relative lightness of the material, allowing efficient industrial prefabrication and consequent productivity benefits.

Assuming the production of coniferous sawnwood were to increase at an annual rate of 1.8% to 2030 (cf. Hildebrandt et al. 2017), and if some of the incremental harvest is used to substitute steel, concrete and bricks in construction, there is a potential substitution benefit of around 89 million tons (Mt) of CO_2eq in 2030. In contrast, focusing on multi-storey residential construction and assuming a 1% increase in global markets for wood use in residential multi-storey construction by 2030, the result would be a modest substitution benefit of 4.4 Mt CO_2eq. These values compare to total global construction-related emissions of 5,700 Mt CO_2 including the use of buildings (Huang et al. 2018), resulting in a 1.5% emission reduction in the construction sector. Indeed, Peñaloza et al. (2018) found that in the case of construction, the priority ought to be to substitute high-impact building types simultaneously with several different approaches to gain optimal climate change mitigation results.

According to the literature, the overall impact of increasing the use of wood may remain modest compared to the overall regional GHG emissions. One of the few EU-level upscaling studies found that a strong increase in material use of wood for construction would result in avoided emissions of

10 Mt CO_2e/yr on average, when compared to a business-as-usual reference scenario (Rüter et al. 2016). Eriksson et al. (2012) estimated that an additional one million apartment flats per year being built out of wood instead of non-wood materials in Europe by 2030, would reduce annual carbon emissions by 0.2–0.5% of the total 1990 European GHG emissions (15.8–35.6 Mt CO_2eq). Only an extreme scenario of an average wood products consumption of 1 m³ per capita throughout Europe – compared to the current level of 0.15 m³/capita in Europe in 2017 (FAOSTAT) – would result in large substitution benefits (605 Mt CO_2eq). Sathre and Gustavsson (2009) presented similar scales for the EU-25, ranging between 0.03–1.2 % for total emissions reduction by using more wood in multi-storey construction. Kayo and Noda (2018) also arrive at similar scales with a maximum substitution benefit of 0.7% of Japan's emissions in 2050 (9.6 Mt CO_2eq/year) for civil engineering, including piles, check dams, paved walkways, guardrails, and noise barriers. These values compare, for example, to the global concrete industry's share of global emissions of around 5%. Of note, these values only refer to substitution impacts and disregard, for example, the carbon storage of HWP.

Textiles

In addition to wood construction, the wood-based textile market has gained interest recently in industry and academia. The textile sector is one of the largest industries in the world with a global raw material consumption of close to 100 million tons. The market is still rapidly growing, mainly driven by increases in population, average income and fashion cycles (Antikainen et al. 2017). The textile market is dominated by synthetic oil-based fibres. The textile industry does make extensive use of natural fibres, notably cotton (25–30% of the textile fibre market) and man-made cellulosic fibres (7%), as well as wool and silk. Even though the production of cotton is stable or even slightly increasing, its relative share is clearly decreasing (Hämmerle 2011). Together with the increasing demand for textiles, there is an opportunity for wood-based textile fibres to gain growing markets (Hurmekoski et al. 2018). Man-made, or regenerated cellulose fibre segment is dominated by wood-based viscose, whose initial production dates back for more than a century. New processes based on alternative solvents are currently being developed to overcome the use of harmful chemicals (carbon disulphide) associated with contemporary viscose production and simultaneously reduce the embodied energy of the production process.

If we consider a scenario in which the production of dissolving pulp would grow at an annual rate of 3.9% up to 2030 (Pöyry 2015), and that 75% of it is used to produce man-made cellulosic fibres, the result would be a possible global substitution benefit of around 11 Mt CO_2eq in 2030. While the textile case is more straightforward compared to construction in terms of determining a functional unit, the lack of data on the emerging regenerated fibre processes pose issues for upscaling. Here, we used Lyocell to approximate the environmental attributes of the emerging regenerated fibre processes, such as IONCELL-F. No studies could be found that quantified the potential substitution benefit of an increased consumption of wood-based textile fibres on a market level.

New products

Within the vision of a future wood-based bioeconomy, the use of wood is expected to expand beyond construction and textiles to new wood-based materials e.g. in packaging applications, bio-based chemicals, biofuels and a large variety of downstream niche markets (Näyhä et al. 2014; Hurmekoski et al. 2018). For example, in future new wood-based application of furfural, which can be converted into more than 80 usable chemicals and could substitute industrial chemicals from petrochemical sources (Dalvand et al. 2018). Such emerging product categories have not been assessed in our review because there are no available studies on substitution factors, as well as a lack of information regarding the substitution process. Whether these emerging products will have lower emissions than alternative products will depend very much on the embodied energy of the new production processes relative to current technology and non-wood innovations.

Increasing demand for single product groups, such as new packaging materials or biochemicals, does not necessarily translate to increased harvests (Rougieux & Damette, 2018; Hurmekoski et al. 2018). This could be due to two reasons. First, digital media development is causing demand for graphic paper to decline at an annual rate of a few percent. The second factor is that by-products of sawmilling and pulping are currently used mostly as energy. They could be increasingly used as a feedstock for other products such as biomaterials, biofuels and biochemicals, if the operating energy for pulp mills and sawmills would be produced by other means, or reduced by increased energy efficiency (Stern et al. 2015). Such dynamics may have important consequences for the overall substitution benefits of wood use in the future. Given that a limited supply of biomass feedstock is needed to satisfy multiple demands for products, consideration needs to be given to the best use of wood to reduce net GHG emissions.

3.3 Substitution as a part of a broader system

Calculating the substitution impacts on a market or regional level only provides one part of the equation for determining the climate impacts of using wood for industrial purposes. Understanding whether changing forest management activities will provide climate benefits in the short to medium term, i.e. in a matter of a few decades, requires adopting an integrated systems approach that considers carbon stock changes in standing forests, soil, and harvested wood products (HWPs), as well as the avoided fossil emissions through substitution. In addition, how the different uses of forests are connected to the long-term ability of forests to sequester carbon and adapt to a changing climate, and how forest disturbances may impact forest carbon sequestration, needs to be considered. While a comprehensive analysis is challenging, a systems approach is required to reveal the potential synergies and trade-offs in mitigation effects across the components of the forest sector, and is useful in defining effective climate change mitigation portfolios (Lemprière et al. 2013; Smyth et al. 2014; Gustavsson et al. 2017).

Studies using forest ecosystem and wood product models suggest that a decrease in the level of harvest and forest products production in the EU is likely to result in an increase in harvests and forest products production in the rest of the world (Rüter et al. 2016). This “leakage effect” may compromise the effectiveness of climate policies regulating land use in the EU (Kallio & Solberg 2018; Kallio et al. 2018) as production emissions could be substantially higher in other locations or other industries. Ultimately, it is necessary to also consider the impacts of carbon leakage on substitution benefits but this adds significant complexity. One remedy can be to focus policies on demand rather than on supply.

4. Substitution effects of using wood products: summary of results

Wood products

The large majority of studies indicate that the **use of wood and wood-based products are associated with lower fossil and process-based emissions when compared to non-wood products**. For example, the use of wood for construction purposes results in climate benefits when compared to non-wood products. Average SF for structural and non-structural construction are 1.3 and 1.6 kg C / kg C wood product, respectively. Substitution benefits are largely gained due to reduced emissions during the production and the end-of life stages, particularly when post-use wood is recovered for energy.

A previous meta-analysis (Sathre & O'Connor 2010) estimated a mean substitution effect of 2.1 kg C / kg C wood product. Based on our review and more recent studies, our **results suggest a lower substitution effect of 1.2 kg C / kg C wood product**. One likely reason for this difference is that most of the studies in the earlier meta-analysis focused on construction materials and covered the full life cycle, while the current meta-analysis contains studies on a more diverse range of material types, and many studies covered only the production stage and excluded other life cycle stages.

The reviewed substitution factors have **substantial variability and uncertainty**, which can be explained by differences in assumptions, data and methods. The results also show that substitution factors are context-specific. A difficulty encountered in the literature review was the lack of detailed information on how the wood products and their substitutes are modelled. Often crucial information is missing and, in several cases, the studies are performed with different levels of transparency. The development and continuous improvement of analysis methods and international standards with regards to LCA will facilitate improved comparison of the environmental performance of wood products in the future.

We also identified **important research gaps that should be covered** to have a better understanding of the substitution effects. Firstly, most studies in the literature focus on construction and significantly less information exists for other product types such as **textiles**. Very limited information exists on the associated emissions and potential substitution effects for **biochemicals**, which are considered an important product in the future bioeconomy (Lettner et al. 2018). Secondly, most available studies focused on North America and the Nordic countries in Europe, and very few studies considered cases from **Asia**, **South America**, **Africa**, or from **south or east Europe**. More studies are needed for better geographical representativeness.

Regional and market level impacts

The overall substitution benefits depend not only on the relative difference in emissions between two alternative products (substitution factor), but also on the **scale of production and consumption** of the products.

Upscaling the substitution benefits on a regional or market level requires an understanding of market dynamics and detailed substitution processes. Given the amount of wood already used for various purposes, it is clear that the total climate benefits from historical material substitution are very large. If wood as a renewable raw material would not have been available, it is likely that other materials would have fulfilled the demand, with a likelihood of higher GHG emissions as a result. However, in order to work towards climate targets, it is not sufficient to look at the substitution benefits that reflect the current or historical situation. Instead, it is important to **focus on the future changes caused by expected increases in market shares of wood products**, new wood-based products, technological changes and the potential additional climate benefits when compared to the current state.

The research literature generally suggests that an increased use of wood contributes to the mitigation of GHG emissions particularly in the building sector. Yet e.g. on the EU level, the relative impact of an increased use of wood in construction would remain relatively modest compared to the overall GHG emissions of the region, unless the **overall use of wood in the markets is much higher** compared to the present volumes.

The use of wood is expected to increase in the future, for example in textiles, packaging, chemicals, biofuels and a large variety of downstream niche markets. In general, the **research literature does not yet capture sufficiently these new and promising**

areas. For example, the possible substitution impacts of packaging paper are not well known due to the extreme diversity of materials in use and the consequent complexity of substitution processes.

Holistic view of mitigation potential is essential

As shown in in this report, **the substitution factor is one necessary, but not sufficien**t, **piece of information needed to assess the role of wood-based products in climate mitigation.** In order to inform policies, one needs also to consider other factors, such as forest carbon sinks, forest soil carbon sink, and harvested wood products carbon storage. One should also consider what is the overall climate mitigation balance between these factors, through questions such as "Is it more efficient to store carbon in forests instead of using forests for products and energy"? The mitigation potential of these two options depends on the magnitude of the substitution factors and losses in forest carbon sinks due to harvesting.

However, in addition to substitution and harvesting, one should also take into account how permanent forest carbon sinks would be. The permanence aspects relate especially to two factors. First, old forests will eventually "decay" and the carbon stored in the old trees will be lost. Second, the older the forests, and the less they are managed, the higher the probability is that they will be affected by disturbances (forest fires, storms, bark beetle outbreaks, etc.). Disturbances may take place also in the very short-term. For example, forest fires and bark beetle outbreaks are already today an increasing source of CO_2 emissions, sometimes around 10-20% of a country's annual emissions (e.g in Canada and Portugal). Moreover, the climate change mitigation potential of forests is married with adaptation to climate change. Tree species, seedlings, and other forest management measures are needed to adapt forests to a changing climate. Forest owners need to have an incentive to implement and fund adaptation measures. The bioeconomy can be one such incentive and funding source.

Climate policy targets need to be considered together with SDGs

It should be emphasized that the current study has focused only on one environmental aspect of wood products, namely climate mitigation potential. Yet, it is important to consider also the impacts of forests on the sustainable development goals (SDGs) in general. The role of wood-based products in helping to phase out plastics and their related environmental problems, or in providing a renewable raw material that can replace non-renewables, are important objectives. Moreover, whatever the materials used in production, resource-efficiency is a key target to help to reduce emissions and material waste.

Finally, it is important to understand that in practice it is often not a question of using wood or other materials, but rather their optimal combination. There are some cases where it simply does not make practical sense to use wood, such as for the foundations of buildings, in which concrete has major advantages. On the other hand, using wood combined with other materials may in some cases be sensible, for example, to provide better properties for concrete, while also helping to reduce the emissions of that material.

5. Policy implications

Substitution factors (SF) assess how much using wood-based raw materials and products instead of alternative materials and products can help to mitigate climate emissions. Our SF review showed that in **most cases the use of wood and wood-based products is associated with lower fossil and process-based emissions when compared to non-wood products. However, the substitution factor alone should not form the basis of policies**, since the overall climate impacts of forest production depend also on forest carbon sinks, forest soil and carbon stored in harvested wood products. It is crucial to consider that the GHG substitution impact of wood products is only one component in climate change mitigation and the GHG emissions balance. Since substitution factors focus usually only on fossil GHG emissions in techno-systems, the climate effects of SF should be considered only as one input, in addition to other factors that affect the climate mitigation impact.

Forest product markets are expected to become more diverse in future decades (Hurmekoski et al. 2018). Important markets for emerging wood-based products include prefabricated engineered wood products for multi-storey construction, consumer packaging and other plastic substitutes, textiles and basic chemicals. These sectors are among the key sectors when looking for large future substitution potential, due to potentially high market volumes and potentially high substitution factors. However, since there is also a considerable **lack of knowledge of the impacts in these emerging areas**, it is difficult to estimate what the overall mitigation impact could be.

Despite uncertainties and knowledge gaps, it is vitally important to realize that substitution factors are not constant at the level of products, regions, or markets. **The substitution factors are likely to change** due to factors such as technological development, product design, improved resource efficiency, recycling and improved end-of-life phase of products. But perhaps even more important is to remember that **the fundamental aim is not to maximize substitution factors as such, but to minimize emissions**. Tools, means and policies to enhance e.g. recycling and resource efficiency often imply smaller emissions for both wood and non-wood based products.

In order to work efficiently towards climate targets, **potential carbon leakages need to be taken into account** as well. Given the increasing global demand for forest products, limiting production in a geographical area such as the EU is likely to lead to increased production in other regions. From the viewpoint of climate mitigation, this may even lead to increasing emissions due to differences e.g. in resource efficiency between different regions. Ultimately, it is necessary to consider also the impacts of carbon leakages on substitution benefits, but again, this adds significant complexity, and is beyond the scope of this study.

Since substitution is only one element in mitigation, it is important to take into account trade-offs and/or synergies between substitution and forest carbon sinks at different timescales. For example, if global demand for bio-products increases and this implies higher harvesting levels, it is important to take into account potential trade-offs between forest carbon sinks and GHG substitution effects. In this context, an important question is how well **substitution factors with existing product portfolios can compensate the potential reduction in sinks.** And moreover, **how the existing product portfolio could be changed to improve the mitigation impacts further?**

Key messages

- Usually wood and wood-based products have lower fossil and process-based GHG emissions when compared to non-wood products.
- The substitution factor is important but does not provide sufficient information to guide policy making. A more holistic analysis is necessary, which also considers forest and forest soil sinks, harvested wood products carbon storage, permanence of forest sinks and forest disturbances, and carbon leakage effects.
- Resource-efficiency and minimizing material waste should be a simultaneous policy target with climate mitigation.
- There is a lack of knowledge on climate impacts of emerging forest products. Research funding should be targeted to this area e.g. in the EU.
- Climate mitigation is one major policy target. When considering the impacts of different materials and products, it is also important to consider all SDGs, aiming to find synergies between the different goals and policy targets and minimize trade-offs.

Glossary

Allocation: Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. Used in Life Cycle Assessment to deal with multi-functional processes (i.e. multifunctionality).

Biogenic carbon dioxide emissions: Emissions to the atmosphere from a stationary carbon source directly resulting from the combustion or decomposition of biologically-based materials other than fossil fuels.

By-product (or co-product): Any of the two or more product-outputs coming from the same unit process or product system.

Carbon dioxide equivalent or CO_2eq: a common unit for different greenhouse gases where CO_2e signifies the amount of CO_2, which would have the equivalent global warming impact.

Greenhouse gases: A greenhouse gas is a gas that absorbs and emits infrared radiation. The main greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone.

Harvested Wood Products (HWPs) are wood-based materials harvested from forests, which are used for products. Wood products contribute to mitigating climate change e.g. through forming a storage pool of wood-based carbon.

Life Cycle Assessment (LCA): Method for analyzing and assessing the environmental impacts of a material, product or service throughout its entire life cycle.

Multifunctionality: multi-functional processes in Life Cycle Assessment are those that have more than one function and deliver several products (e.g. the process of sawmilling delivers sawnwood and sawdust).

Product system: System of consecutive and interlinked unit processes (subsystems), which models a product life cycle.

Substitution factor (or displacement factor): express the GHG efficiency of using a wood-based product to reduce GHG emissions to the atmosphere compared to a non-wood based equivalent alternative product.

System boundaries: A concept used to define and integrate or exclude the unit processes, entities or activities that will be considered in Life Cycle Assessment.

System expansion: Changes in the system boundaries of the studied system to include additional functions related to co-products. Used in Life Cycle Assessment to deal with multi-functional processes (i.e. multifunctionality).

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We are living in a time of accelerated changes and unprecedented global challenges: energy security, natural resource scarcity, biodiversity loss, fossil-resource dependence and climate change. Yet the challenges also demand new solutions and offer new opportunities. The cross-cutting nature of forests and the forest-based sector provides a strong basis to address these interconnected societal challenges, while supporting the development of a European circular bioeconomy.

The European Forest Institute is an unbiased, science-based international organisation that provides the best forest science knowledge and information for better informed policy making. EFI provides support for decision-takers, policy makers and institutions, bringing together cross-boundary scientific knowledge and expertise to strengthen science-policy dialogue.

This work and publication has been financed by EFI's Multi-Donor Trust Fund for policy support, which is supported by the Governments of Austria, Czech Republic, Finland, France, Germany, Ireland, Italy, Lithuania, Norway, Spain and Sweden.

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