Food and Agricultural Organization of the United Nations

Forest Products and Statistics Team

Carbon Storage and Climate Change Mitigation Potential of Harvested Wood Products

Background Paper prepared for the

61st Session of the FAO Advisory Committee on

Sustainable Forest-based Industries

April 2021

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Acknowledgements

This background paper has benefited from the ideas and support of Thaís Linhares-Juvenal, Sven Walter, Pierre Bouillon, Arvydas Lebedys, Lyndall Bull, Marieke Sandker, Francesca Bertola, and Dina Moawad of FAO as well as Sandro Federici previously with FAO. Frits Mohren, Leam Martes, and Richard Sikkema, Wageningen University, The Netherlands, contributed to the paper with analysis and/or review. Federico Alice Guier, Wageningen University and Universidad Nacional, Costa Rica also provided essential inputs and review. Kenneth Skog, US Forest Service (retired), Werner Kurz, Natural Resources Canada, Bruce Lippke, University of Washington (Professor Emeritus), Mariana Hassegawa and Pieter Johannes Verkerk, European Forest Institute, and Sebastian Rüter, Thünen Institute of Wood Research, provided resource materials and review of early ideas or final drafts that substantially improved the manuscript. Members of the Advisory Committee on Sustainable Forest-based Industries (ACSFI) provided early review and feedback that also improved the manuscript. All errors remain with the author.

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Acronyms

ACSFI	FAO Advisory Committee on Sustainable Forest-based Industries
EPD	Environmental Product Declaration
FAO	Food and Agricultural Organization of the United Nations
FCBA	French Institute of Technology for Forest-based and Furniture Sectors
HWP	Harvested wood products
IGS	Institute for Global Environmental Strategies
INDC	Intended nationally determined contributions
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KP	Kyoto Protocol
LCA	Life cycle analysis
LULUCF	Land Use, Land Use Change and Forestry
SDG	Sustainable development goal
UNFCCC	United Nations Framework Convention on Climate Change

Measurements

C	carbon
Ce	carbon equivalent
CO2	carbon dioxide
CO2e	carbon dioxide equivalent
Gt	gigatonnes = billion MT
Gg	gigagram = billion grams = 1000 MT
kt	kilotonne = 1000 MT
Mg	megagram = metric tonne = MT
M	million
MT	metric tonnes
Mt	megatonnes = terragrams = M MT
Pg	petagrams = 1000 M MT
ppm	parts per million
Tg	teragrams =megatonnes = M MT

Carbon Storage and Climate Change Mitigation Potential of Harvested Wood Products: Executive Summary

This report was prepared for the Advisory Committee on Sustainable Forest-based Industries (ACSFI) of the Food and Agriculture Organization of the United Nations (FAO). The purpose of this report is to summarize the state of knowledge on carbon storage and the climate change mitigation potential of harvested wood products (HWP). While there is general consensus that HWP have the potential to reduce carbon emissions and contribute to climate change mitigation strategies, there is confusion surrounding the pathways by which those benefits can be accrued and the types of analyses which can be used to quantify benefits. There exist a large number of studies reporting on the climate change mitigation potential of HWP but each study uses a somewhat different methodology; studies rarely report outcomes in the same units; and studies may report on different types of mitigation pathways.

This background paper aims to capture what is known, describe what remains uncertain, and identify the most critical knowledge gaps in quantifying the climate change mitigation potential of HWP. The main discussion points are summarized below.

- HWP production and use has the potential to reduce greenhouse gas (GHG) emissions through direct carbon storage, substitution of non-renewable materials, and increased availability of biofuels.
- Wood and HWP can contribute to the achievement of multiple sustainable development goals (SDGs) including the promotion of sustainable economic growth, combating climate change and its impacts, and the protection, restoration and promotion of the sustainable use of terrestrial ecosystems.
- Most but not all studies to date, across countries and continents, have indicated that use of HWP can reduce carbon emissions in both the long and short term but considerable uncertainties remain.
- Good practice guidance from the IPCC describes the importance of understanding the influence of uncertainties on estimates of both the magnitude of absolute values and of trends in greenhouse gas inventories for UNFCCC reporting and associated technical work.
- The considerable range in estimates of carbon emissions associated with storage of carbon in HWP results from (a) unknowns associated with end-of-life pathways, (b) the range of methods used in estimating carbon storage within HWP, and (c) uncertainties in input values, e.g., national estimates of HWP activity, conversion factors, and half-lives for HWP categories.
- Uncertainties in the calculation of total carbon emission changes associated with production and use of HWP also include uncertainties associated with definitions, model formulation, and analysis boundaries.
- Accurate, precise, transparent, and complete estimates of carbon storage in HWP over time and by country can aid in supporting effective international agreements on managing greenhouse gas emissions and in identifying and incentivizing sustainable development strategies.
- Opportunities for future work include supporting countries across all geographical areas in estimating carbon storage in HWP, accounting for and reducing uncertainties, expanding analysis frameworks to include emerging forest products, and supporting a wide-range of analyses to quantify the changes in GHG emissions resulting from production and use of forest products.

Introduction

- Background

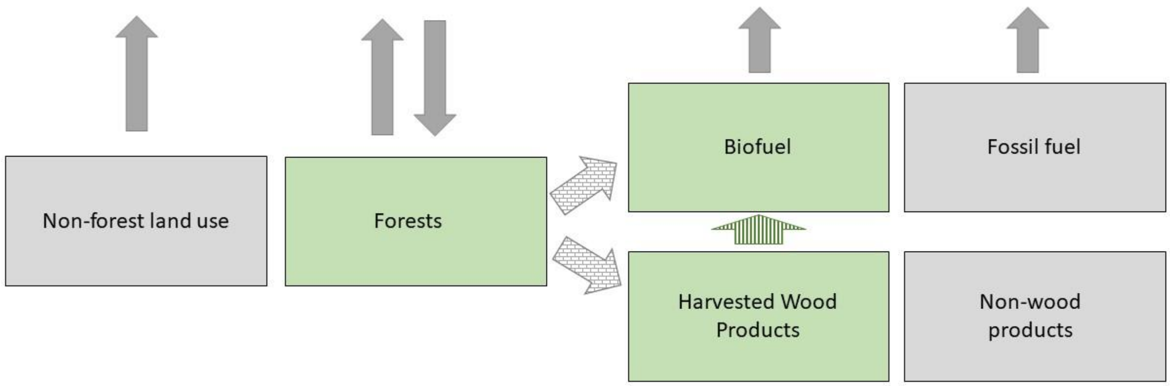
This report, prepared for the Advisory Committee on Sustainable Forest-based Industries (ACSFI) of the Food and Agriculture Organization of the United Nations (FAO), summarizes the state of knowledge on the carbon storage and climate change mitigation potential of harvested wood products (HWP). The focus is on accounting for carbon storage in HWP as well as carbon emission reductions achieved when HWP are substituted for more carbon intensive materials and as a result of increased availability of biofuel (Figure 1). While there is general consensus that HWP have the potential to provide climate change mitigation benefits, there is confusion surrounding the pathways by which those benefits can be accrued and the types of analyses which can be used to quantify benefits. There exist a large number of studies reporting on the climate change mitigation potential of HWP, but each study uses a somewhat different methodology; studies rarely report outcomes in the same units; and studies may report on different types of mitigation.

FAO has a particular interest in the topic as custodian of the forest product statistics database discussed by the IPCC for use in estimating carbon storage within HWP (IPCC 2019). This background paper aims to capture what is known, describe what remains uncertain, and identify the most critical knowledge gaps in quantifying the climate change mitigation potential of HWP. The work aims to contribute to improved communication on the topic and to indicate directions for further work.

At the beginning of the industrial era, circa 1750, the concentration of carbon dioxide (CO2) in the atmosphere was approximately 277 parts per million (ppm) (Joos and Spahni 2008). This value had risen to 413 ppm by 2017 (ESRL 2020). The Kyoto Protocol (KP) operationalizes the the United Nations Framework Convention on Climate Change (UNFCCC) by committing industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets. The Paris Agreement, adopted in 2015 by 195 Parties to the UNFCCC, recognizes the urgency of reducing emissions to mitigate climate change, calls for limiting future increases in global temperatures, and recognizes the key role of forests in both mitigation and adaptation. To meet the aspirations of the Paris Agreement, countries contribute to emission reduction on the basis of voluntary commitments expressed as intended nationally determined contributions (INDCs).

More than 70 percent of the countries that submitted INDCs to UNFCCC included forests in their planned contributions to mitigation. Many countries also recognized the role of forests in adaptation. Forests store carbon in the soils and in the trees. When a tree is harvested, the carbon is no longer stored in the forest but may remain in the wood, in other biotic materials, and in the HWP eventually produced from these raw materials. Countries in a position to do so may report on HWP as part of their INDCs under the land use, land-use change, and forestry (LULUCF) sector. The Intergovernmental Panel on Climate Change (IPCC 2006) provides good practice guidelines for estimating carbon emissions and removals from HWP which were revised after the KP (IPCC 2014); additional refinements to these guidelines were produced in 2019 (IPCC 2019).

Figure 1: The scope of this review in the context of carbon emissions and carbon storage in forestry and associated alternatives. Green boxes contain systems directly related to forestry; grey boxes contain systems whose emissions may change when forestry systems change. Solid grey arrows represent carbon exchanges with the atmosphere; brick-patterned arrows indicate flows of wood carbon; green arrows indicate flows of wood carbon. The striped arrow indicates that waste from the production of harvested wood products (HWP) leads to increased availability of wood materials for biofuels. This review focuses on the emissions reduction potential of HWP through carbon storage with some discussion of emission reduction potential through substitution of other more carbon-intensive materials and through increased availability of biofuels with only tangential mention of other areas represented in this figure such as carbon sequestration by forest re-growth. Modified from Vose et al. (2012), Figure 4.13.



Harvested wood products can directly influence energy and greenhouse gas (GHG) balances in three ways. First, products made of wood can physically store carbon and thus expand carbon storage outside of the forest. Second, the production of wood increases the availability of biofuels which can be used in place of non-renewable energy sources. And, third, wood can substitute for more energy-intensive and non-renewable materials such as cement, steel and plastic. Cement-making, for example, accounts for six percent of the world's carbon emissions; steelmaking produces 8 percent of the world's carbon emissions and half of the steel produced goes into buildings (The Economist 2019). Early estimates indicated that a global shift toward more wood products in building construction could reduce annual emissions by as much as 66 M MT C (reported as 66 million tonnes C) and increase annual contributions to long-term storage of carbon by as much as 15 M MT C (reported as 15 t C (millions)) (Buchanan and Levine 1999).

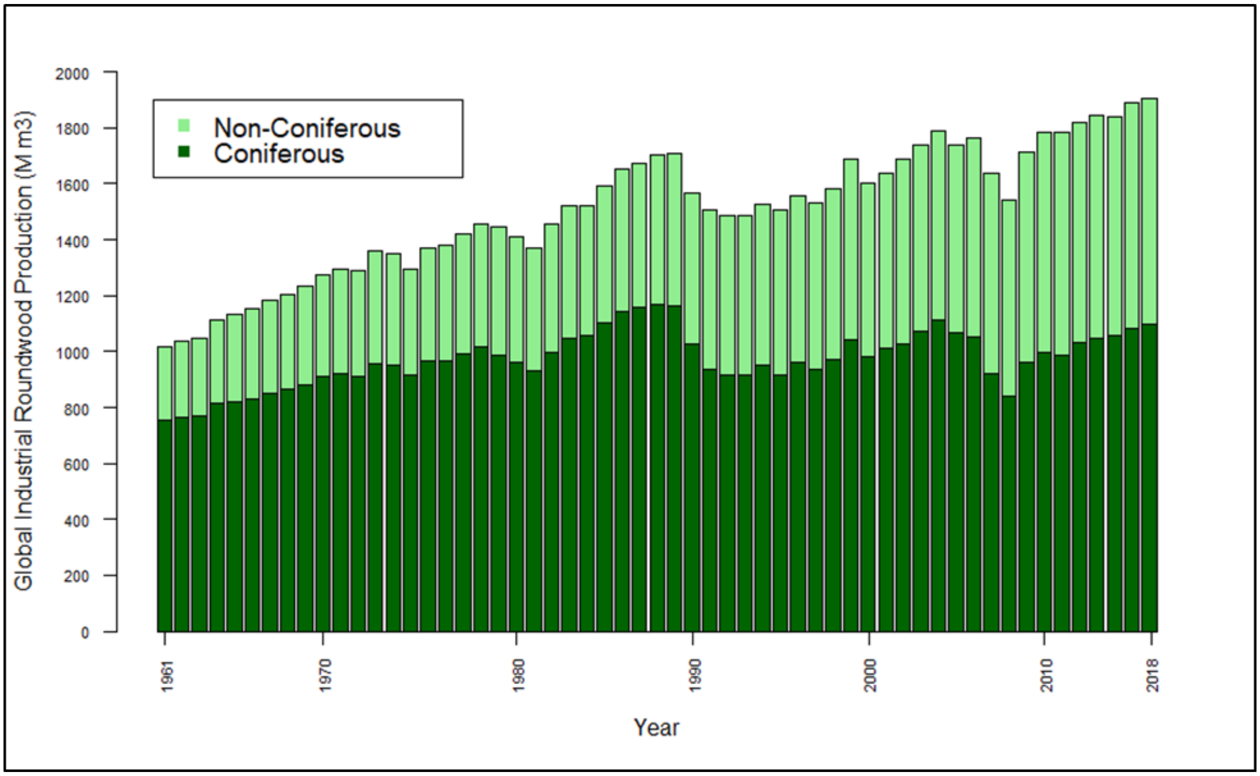
The global stock of carbon within forest products was first estimated at 4 100 to 20 000 M MT C (reported as 4 100 and 20 000 teragrams (Tg) C), with net sink rates of 26 to 139 M MT C per year (reported as 26, 139 Tg C) (Larson 2012). Since then, a wide range of global and national estimates have been produced (see section on "Climate Mitigation Potential of Harvested Wood Products"). The wide range in estimates of carbon emissions associated with carbon storage in HWP results from (a) unknowns associated with end of-life pathways, (b) the range of methods used in estimating carbon storage within HWP, and (c) uncertainties in input values, e.g., national estimates of HWP activity, conversion factors, and half-lives for HWP categories. Conversion factors link the volume of each HWP category to the mass of carbon stored. The half-life of carbon stored in a particular pool is defined as "the number of years it takes to lose one-half of the material currently in the pool" (IPCC 2006) and provides an index of how long carbon is expected to be stored in a particular product type. Default conversion factors are available for HWP categories and subcategories (IPCC 2019) and default half-lives are provided by the IPCC (2019) for three semi-finished HWP categories.

Studies that include carbon mitigation effects of HWP may include multiple types of effects. It is noted that a full summary of the evidence across studies and regions necessarily includes studies on carbon storage in HWP, studies on substitution effects, and studies that merge the two. Therefore, in places, the summaries below also merge discussion of the two types of climate mitigation that may arise from the use of HWP. Additionally, because results are reported in a wide variety of units, they were converted to MT for comparison where possible (units and values originally reported are provided parenthetically). Where units are not converted to MT, it indicates that results are not easily comparable.

- Global Trends in Harvested Wood Products

Global production of industrial roundwood, which may be used to produce semi-finished wood products, has been growing since 1961 (Figure 2). The production of coniferous wood continues to be higher than that of non-coniferous wood; however, the share of non-coniferous wood has been steadily increasing. For this report, all available data are displayed for the most comprehensive synthesis possible; however, in general, when looking at long time-series of data many factors may influence apparent trends including progressive improvements in reporting (IPCC 2019). In the case of forest products, apparent trends may be influenced by reporting thresholds. Although international reporting requests to countries are for all production, in some countries and for some products, wood processing mills may be required to contribute national data only if they exceed a certain threshold size. As the distribution of capacities shifts over time, then also the proportion of production reported at the national level might shift which might then also be reflected in international statistics. Additionally as statistical capacity increases within and across countries, one might expect a higher and higher proportion of production to be recorded and included in global totals.

Figure 2: Global trends in industrial roundwood production.
(FAOSTAT, http://www.fao.org/faostat/en/#data/FO)



Transparent and verifiable activity data for sawnwood, wood-based panels and paper and paperboard are required to apply IPCC guidance for estimating carbon storage in HWP using first-order decay equations (see below). Global production of sawnwood has increased slowly over time with a stronger upward trend in recent years. The proportion of non-coniferous sawnwood has remained relatively steady over the past fifty plus years and has also seen an increasing trend developing in the last decade. Veneer sheet production increased dramatically at the beginning of the century and has remained steady since while production of wood-based panels has climbed rapidly in the past twenty years (Figure 3). Global trends in paper production have risen steadily over the available record (Figure 4). It is noted that increases in production of HWP are not necessarily linked to forest degradation or deforestation. In fact, it is challenging to make such links. By definition, deforestation is "the conversion of forest to other land use independently whether human-induced or not" and "the term specifically excludes areas where the trees have been removed as a result of harvesting or logging, and where the forest is expected to regenerate naturally or with the aid of silvicultural measures" (FAO 2018). Forest degradation, on the other hand, was defined as "the reduction of the capacity of a forest to provide goods and services" (FAO 2012) and can now be defined by individual countries (FAO 2018). Less is known about how production of HWP may or may not be linked with forest degradation (Ramage et al. 2017).

Figure 3: Global trends in wood production tied to harvested wood products. Note differences in y-axes. (FAOSTAT, http://www.fao.org/faostat/en/#data/FO)

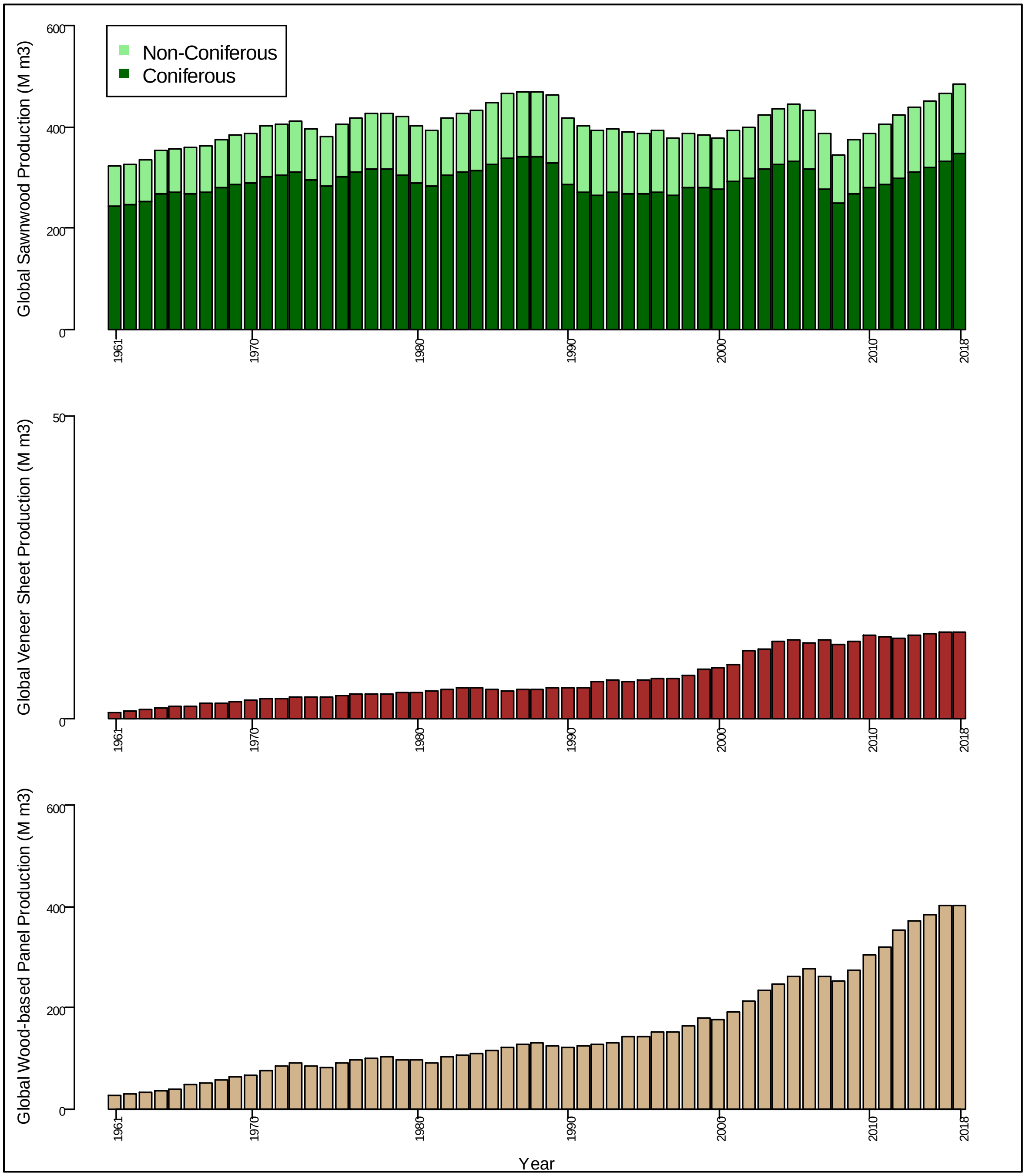
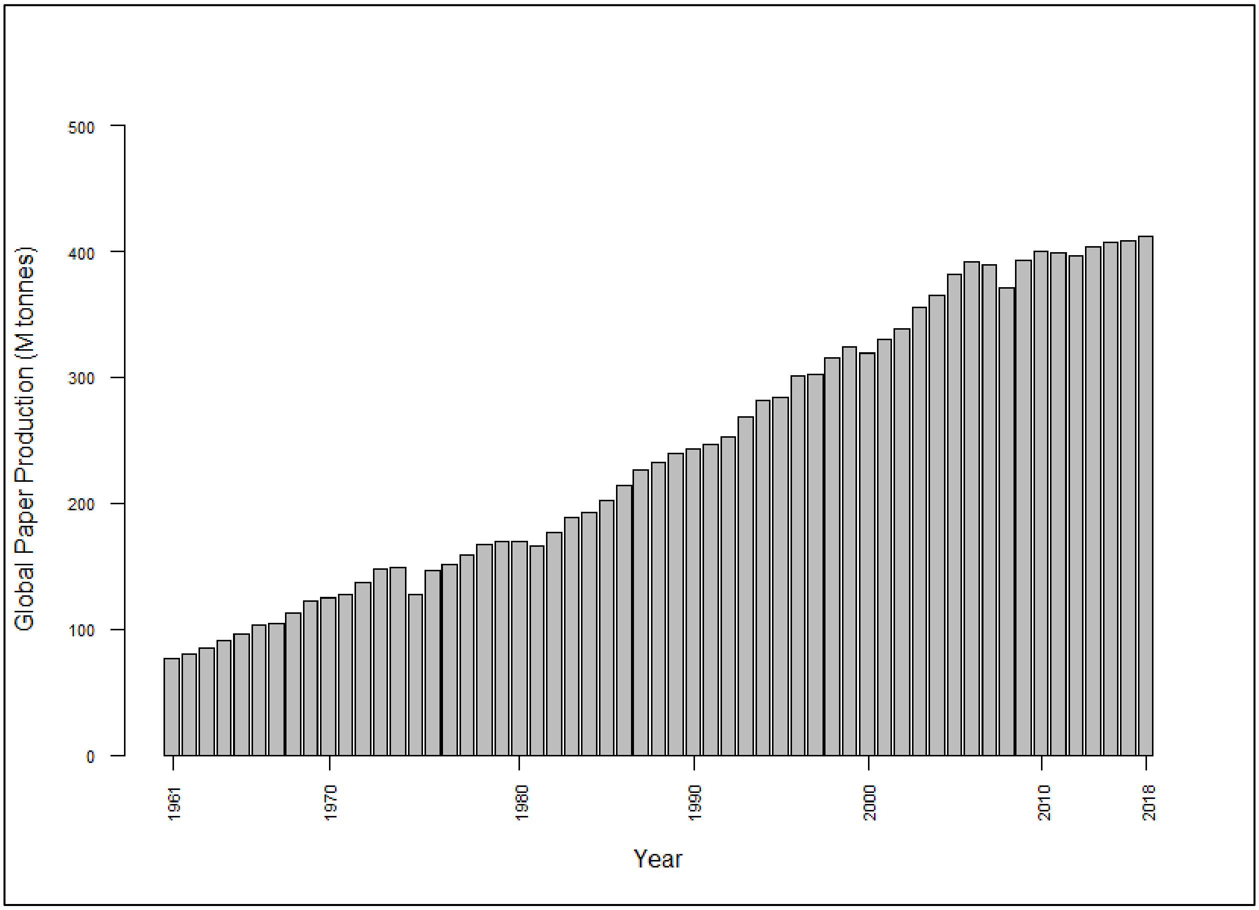


Figure 4: Global trends in paper production. (FAOSTAT, http://www.fao.org/faostat/en/#data/FO)



Contribution of Harvested Wood Products to the Sustainable Development Goals

Improved capacity to quantify the climate change mitigation potential of HWP is likely to lead to increased activity in businesses and markets associated with the production and sale of sustainably sourced and produced wood products and also with the coordinated and sustainable management of forested ecosystems. Done successfully, these activities can support a wide range of sustainable development goals (SDGs) from the promotion of sustainable economic growth (Goal 8) to urgent action to combat climate change and its impacts (Goal 13) to the protection, restoration and promotion of the sustainable use of terrestrial ecosystems (Goal 15). One of the key messages of a recent meta-analysis of substitution effects on carbon emissions from wood and wood-based products is that, in addition to climate mitigation, it is important to consider all of the SDGs and to identify synergies (Leskinen et al. 2018). A few of the clearest connections are detailed below in the context of documented progress or concerns in achieving the 2030 Agenda for Sustainable Development (United Nations 2018).

Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all. While in 2016, real gross domestic product (GDP) per capita grew at 1.3 percent globally, the rate fell from 5.7 percent in 2005–2009 to 2.3 percent in 2010–2016 for the least developed countries (United Nations 2018). Many of the least developed countries could capitalize on opportunities to develop a viable and sustainable forest product sector to support domestic economic growth.

Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. Globally, the carbon intensity of industry decreased from 0.38 to 0.31 kilograms of carbon dioxide per dollar of value added, a reduction of 19 percent from the year 2000 to 2015 (United Nations 2018). Promotion of sustainably produced wood products has the potential to further reduce the per dollar carbon intensity of global industries.

Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
Goal 12: Ensure sustainable consumption and production patterns. The per capita "material footprint" of developing countries grew from 5 MT (reported as 5 metric tons) in 2000 to 9 MT (reported as metric tons) in 2017, representing a significant improvement in the material standard of living and pointing toward growth in the areas of infrastructure and construction (United Nations 2018). Sustainably sourced wood construction can contribute to the continued sustainable development of urban areas in developing countries. Wood used in construction provides the longest carbon storage possible in HWP and potentially the greatest climate impact through substitution effects.

Goal 13: Take urgent action to combat climate change and its impacts. HWP are currently estimated to provide net sink rates of 26 to 139 M MT C per year (reported as 26 139 Tg C) (Larson 2012) and improved accounting could provide incentive for even higher rates of climate change mitigation.

Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. The Earth's forested area continues to shrink, down from 4.1 billion hectares in 2000 (or 31.2 percent of total land area) to about 4 billion hectares (30.7 percent of total land area) in 2015 (United Nations 2018). While the rate of net global forest loss has slowed down by more than 50 percent (FAO 2016a), forest degradation continues to be a concern. Deforestation and land degradation are not, as described above, necessarily linked to forestry activities. Incentivizing the sustainable management of forests could contribute to reductions in the rate of forest loss and degradation.

The above connections are clear and well-defined. Additional tangential opportunities also exist. For example, development of the wood products industry through sustainable forest management and in coordination with efforts to improve land tenure and business opportunities for woman could lead to improvements in the proportion of total agricultural population with ownership or secure rights over agricultural land and even to an increased share of women among owners or rights-bearers of agricultural land (**Indicators 5.a.1 (a) and (b)**). Support to least developed countries in building sustainable forest product value chains can reduce inequality within and among countries (**Goal 10**). Implementation of sustainable forest practices can contribute to ensuring the availability and sustainable management of water and sanitation for all (**Goal 6**) through protection and restoration of water-related ecosystems, including forests (**Goal 6.6**). Finally, improvements in the ability to quantify and account for carbon storage in HWP can provide strong support to strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development (**Goal 17**). For example, mobilization of additional financial resources for developing countries from multiple sources (**Goal 17.3**) and enhancing data, monitoring and accountability (**Goals 17.18 and 17.19**).

Estimating Carbon Storage in Harvested Wood Products

- Methods for Estimating Carbon Storage in Harvested Wood Products

Parties to the KP who agreed to take on commitments during the second commitment period (1 January 2013 to 31 December 2020) are required to account for HWP on the basis of the change in the HWP pool, provided that transparent and verifiable activity data are available for the three HWP categories (Decision 2/CMP.7). The IPCC outlines several tiers of methods for estimating carbon in HWP (IPCC 2006; IPCC 2014; IPCC 2019); the methods themselves are described below, rather than the tiers.

The most basic approach assumes instantaneous oxidation of carbon when a tree is harvested. It is essentially a default assumption of no change in the carbon stock as a result of HWP or no net-emissions from HWP. Under the KP supplement, this approach is considered good practice only in the case that transparent and verifiable activity data for the three default HWP categories, sawnwood, wood-based panels and paper and paperboard, are not available (IPCC 2014).

Generally, simple methods based on first-order decay equations are indicated when there are transparent and verifiable activity data for sawnwood, wood-based panels and paper and paperboard; however, there is not adequate country-specific data for advanced methods. "The availability of data for the above three aggregate HWP commodities in publicly available databases of international organizations, such as FAOSTAT, qualifies for estimating CO2 emissions and removals from HWP on the basis of the 'production' or the 'stock-change' approaches" (IPCC 2019). First-order exponential decay equations are employed using default conversion factors for the three major HWP commodity classes as well as sub-classes for which disaggregated data are available (Volume 4, Table 12.2; IPCC 2019) and default emission factors, expressed as half-lives (Volume 4, Table 12.3, IPCC 2019). Where additional data or information are available, advanced methods may be applied and might include, for example, country-specific models, disaggregated half-life estimates, or additional sources of activity data.

- Accounting Approaches for Estimating Carbon Emission Changes Associated with Harvested Wood Products

There are four main accounting approaches for tracking stored carbon in HWP (Table 1). The conceptual framework differentiates approaches based on stock-changes (**stock-change** and **production**) and approaches based estimates of CO2-fluxes (**atmospheric-flow** and **simple-decay**). The key difference between the two approaches is that the conceptual framework of the stock-change approach is based on changes in carbon stocks in HWP and that of the atmospheric-flow approach is based on identifying and quantifying actual CO2 fluxes from and to the atmosphere associated with HWP. These two types of approaches also differ in how roundwood and fuelwood are considered.

The **production approach** and **simple-decay approach** consider HWP produced in-country, regardless of where products are consumed. Both approaches consider all carbon stored in HWP produced in-country and therefore exclude imports to the target country and include exports from the target country, which are particularly difficult to track. The production approach effectively considers all HWP originating from forests within the country; HWP activity data could, therefore, potentially be assigned to the particular land use category from which the carbon originates within the country. If the simple-decay approach is applied, it is good practice to estimate the annual carbon fluxes into the atmosphere along the timber processing and wood utilization chain within the country. Further activity data are required, covering both feedstocks for processing wood for its use as a material and wood biomass burnt for energy purposes. As above, the key difference between the approaches is that the production approach is based on changes in carbon stocks in

HWP and the simple-decay approach is based on identification and quantification of actual CO2 fluxes from and to the atmosphere associated with HWP. The **stock-change** and **atmospheric-flow** approaches consider HWP consumed in country, regardless of where they are produced (Table 1).

Table 1: Accounting methods for estimating carbon storage in harvested wood products (HWP). The two grey rows indicate whether exported and imported wood products are considered. The two lower rows distinguish the two conceptual frameworks. The two columns distinguish the boundaries of the assessment. Inside the focal four squares are the names of the accounting methods.

	Where are HWP reported?	
	Where they are **consumed**	Where they are **produced**
Exports	Not included	Included
Imports	Included	Not included
Changes in carbon stocks within HWP	Stock-change	Production
Identifying and quantifying actual CO2 fluxes	Atmospheric-flow	Simple-decay

Most published reports and common sense suggest that estimates differ with reporting approach. Clearly policy implications of reporting approach differ dramatically depending on whether the carbon storage or the substitution effect is accounted for in the producing or consuming country (Nabuurs and Sikkema 2001). It is noted that the climate benefits of substitution, e.g., replacing cement with wood, are accounted for in the country that does so but in sectors other than forestry. More detailed guidance on the treatment of CO2 emissions from wood biomass burnt and used for energy purposes is provided in the most recent IPCC refinement (2019).

Uncertainties in Estimating Carbon Storage in Harvested Wood Products

It is good practice that uncertainties are identified, quantified and reduced as far as is practicable and that all information on anthropogenic GHG emissions by sources and removals by sinks which result from mandatory and elective activities are reported with levels of confidence (IPCC 2014). Beyond reporting requirements, it is good statistical practice to include an indication of uncertainty when providing estimates, particularly when providing estimates of quantities relevant to policy-making. In the case of estimate the carbon storage potential of harvested wood products, the potential magnitude of the uncertainty in most estimates is not well understood.

- Sources of Uncertainties

There are many uncertainties associated with estimates of carbon storage in HWP including uncertainties in input values, e.g., national estimates of HWP activity, conversion factors, and half-lives for HWP categories, the accounting method applied (whether or not it is calculated for the purpose of international reporting), the initialization of the model, and the number of separate HWP categories in the model. Results can differ between analyses using default assumptions with simple accounting methods versus those using country-specific data and more advanced methods (Jasinevičius et al. 2018). Depending on the accounting approach applied, additional uncertainty is likely to be introduced in the accounting of international trade to quantify import and export of roundwood and semifinished wood products. In particular, the simplifying assumptions provided by the IPCC (2019) and applied by Mohren et al. (unpublished, described below) may induce biases when imports or exports comprise a substantial part of the production data as reported by FAOSTAT and/or domestic production is fluctuating between years.

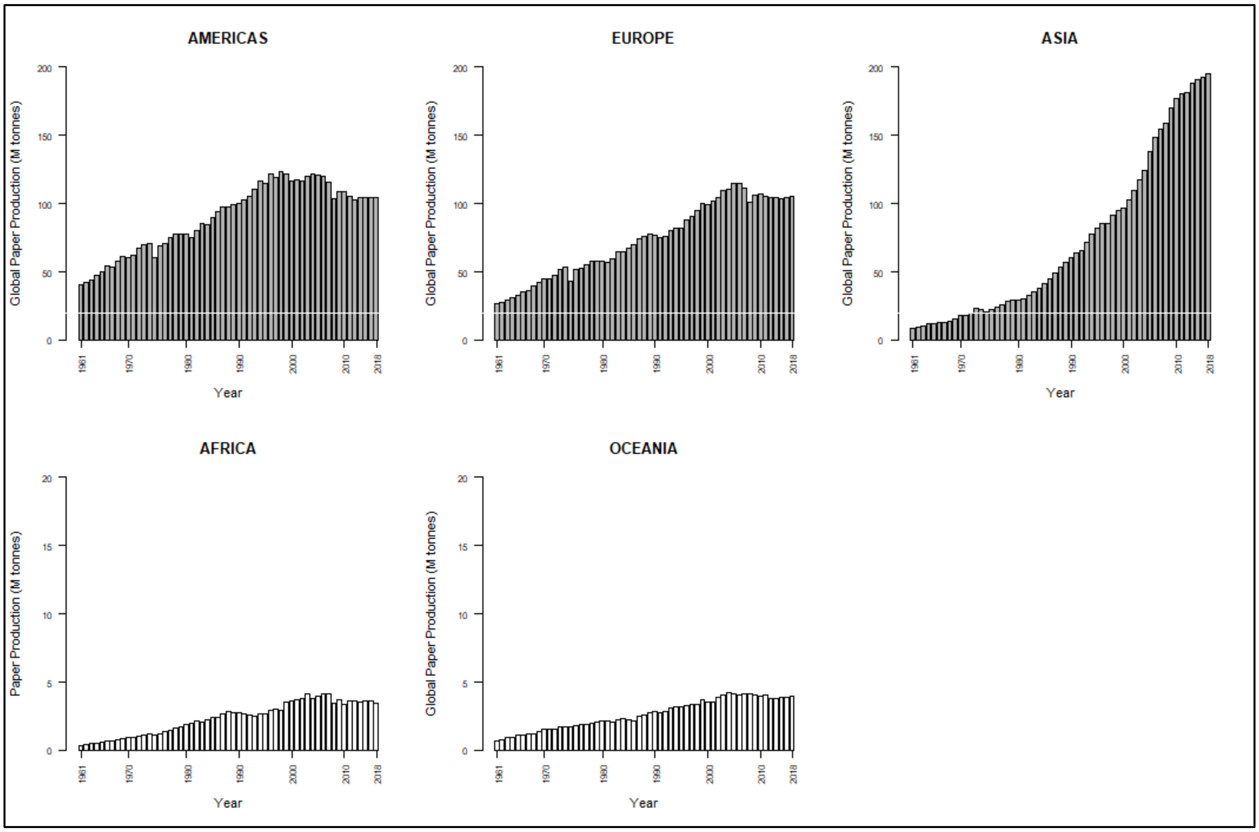
There are often uncertainties and biases associated with missing or inaccurate activity data (IPCC 2014). Uncertainties in activity data (e.g., FAOSTAT data) can arise from unavailability of older data, lack of conformation to definitions, non-representativeness of data collection which may or may not shift over time, double-counting, reporting errors, and challenges in consistently aggregating products (IPCC 2019). Direct and indirect incentives to produce official figures which display positive results and minimize negative consequences must always be considered. Information associated with national estimation and survey procedures, including sampling design, measurement protocols, and quality assurance quality control routines is necessary for assessing the accuracy and precision of activity data (Birigazzi et al. 2019).

There is uncertainty in the half-lives used to estimate the decline in carbon stored in HWP as the products themselves decay. Clearly half-lives for HWP differ by product as in the default estimates provided by the IPCC (Table 2). Half-lives would also be expected to differ by wood species with coniferous and non-coniferous species having, on average, quite different decay rates and by location, with faster decay rates in tropical versus temperate areas. The increasing shift toward production of non-coniferous wood (Figure 2) and the vastly different regional trends in, for example, paper production (Figure 5) suggest that global default decay rates will be insufficient. There is a need to consider variation in decay rates carefully. IPCC (2019) guidance includes the possibility of replacing default half-lives with country-specific half-lives provided there is verifiable and transparent information.

Table 2: Default half-lives for harvested wood product (HWP) categories from IPCC 2019.

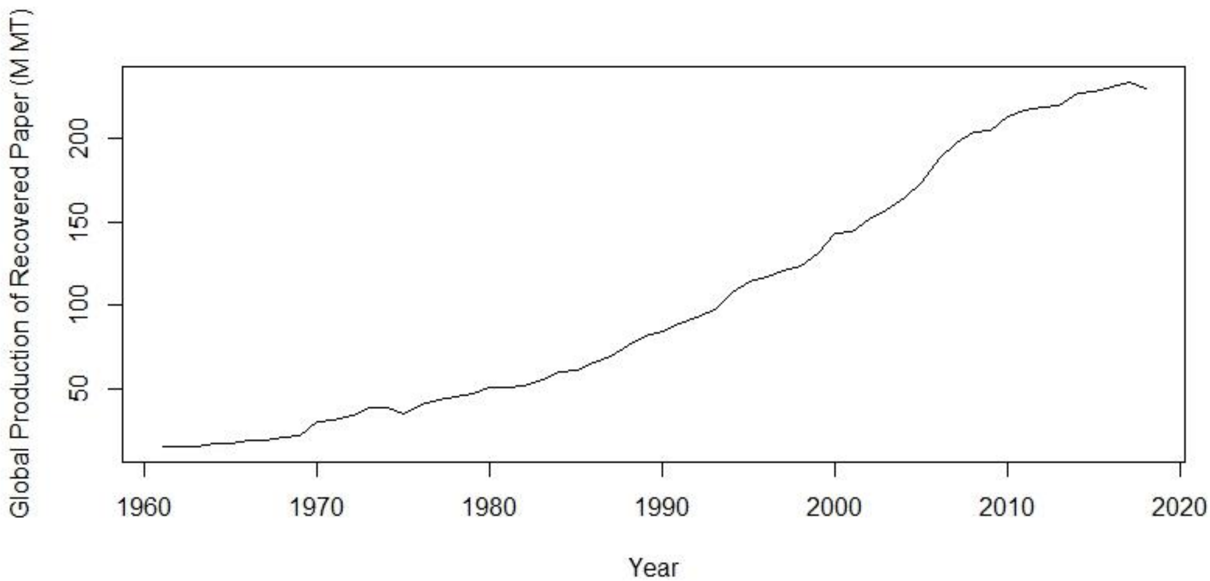
HWP category	Default half-live (years)
Paper	2
Wood panels	25
Sawnwood	35

Figure 5: Regional trends in paper production. Note that maximum value of the y-axis of lower graphs is 0.1 of the maximum of the y-axis on the upper graphs and is denoted by a white line on the upper graphs (FAOSTAT, http://www.fao.org/faostat/en/#data/FO).



Uncertainties also exist in how best to incorporate recycling. Global production of recovered paper has been steadily increasing over the past 60 years (Figure 6). Since 2008, annual global production of recovered paper has been higher than 200 M MT (reported as tonnes). Production and consumption of recovered paper will lead to increased carbon storage times, increased half-lives, and increased opportunities for substitution of more carbon intensive materials. Non-paper products can also be recycled. For example, sawnwood can be recycled into a wood-based panel. Unevenness in the distribution of both production and consumption of recovered products across regions and countries makes incorporation of these factors challenging. Newly available data on post-consumer recovered wood through FAOSTAT will enable additional fine-tuning of national half-life estimates for wood panels and sawnwood.

Figure 6: Global trends in production of recovered paper.
(FAOSTAT, http://www.fao.org/faostat/en/#data/FO)



While few studies have focused on the influence of uncertainties in carbon estimation, some papers have demonstrated that estimates of carbon storage in HWP from advanced methods were more precise than those from first-order decay methods and also point to larger estimates of carbon accumulation using country-specific versus default values (Dias et al. 2009). Across developed countries, specialized conversion factors may be available and these would be expected to have a strong influence on final results. For example, the French Institute of Technology for Forest-based and Furniture Sectors (FCBA) produces a small annual fact book, Memento (available at www.fcba.fr). For 2018, conversion coefficients were provided indicating 1 tonne of dry wood is equivalent to 500 kg of carbon and 1 tonne of carbon corresponds to 3.67 tonnes (0.000004 M MT) of CO_2 as well as species-specific conversion factors for roundwood weights and volume that remain relatively unchanged year to year but which, of course, differ from conversion factors employed by other agencies or analysts. Although uncertainties in any one year may be on the order of 20 percent or more for developed countries and are likely much higher for less developed countries, early estimates suggested that the uncertainty in emission trends was likely to be less than the uncertainty in the absolute value of emissions in any year (IPCC 2001).

A recent report (McGlynn et al. 2019) identified the largest sources of uncertainty and emitted greenhouse gas fluxes in the LULUCF sector of the USA National Greenhouse Gas Inventory. Of all the potential uncertainties in estimating greenhouse gas emissions in the forest sector, for the USA, sampling error in estimating forest tree biomass was the highest and an order of magnitude higher than uncertainties related to estimates of carbon storage in HWP. However, uncertainties in solid wood products data, conversion factors for estimating carbon within solid wood products, uncertainties in paper data, and conversion factors for estimating carbon within paper ranked 7th, 8th, 10th and 12th respectively among a large number of potential parameters and model inputs.

- Uncertainties in Estimating the Full Climate Change Mitigation Potential of Harvested Wood Products

A complete accounting for GHG emission changes associated with production and use of HWP products is challenging as it includes both carbon storage and substitution effects, substitution of wood for more carbon intensive products. Estimates of all potential emission changes associated with production and use of HWP also depend heavily on the baseline, methods, boundaries, and assumptions used to account for changes in forest attributes as a response to increased harvest rates (Gustavsson and Sathre 2006; Upton et al. 2008) as well as economic assumptions (Howard et al. 2021) and assumptions about manufacturing (Dymond 2012).

Since 2011, international standards on competitive life cycle analyses (LCA) for the building sector (wooden and conventional buildings) have been introduced in some countries (e.g. ISO 14040/44 https://www.iso.org/standard/37456.html). In general, and beyond the industry specifications, LCA can generally be classified into two types. A consequential LCA estimates the change in emissions associated with the change in the system operation to produce a particular amount of wood product. An attributional LCA estimates the absolute quantity of emissions (positive or negative) associated with producing a particular amount of wood product over a given time frame.

Other types of published and quoted research for decision-making and for policy-making also aim to capture a more complete picture of the impact of production and use of HWP on GHG emissions. A full description of all possible types of analyses that consider the full impact of forest products is not possible in this synthesis but a consideration of key uncertainties is presented here. Depending on the boundary conditions defined, analyses aimed at understanding carbon storage impacts of HWP, from production to disposal, might include effects beyond direct changes in carbon fluxes associated with production and disposal such as changes in the carbon pools of forests, shifts in markets for wood products, and the opportunity to substitute wood for more energy-intense materials including fossil fuels. Such comprehensive analyses for wood-based systems are extremely complex as a result of (a) the long time-frames involved in both forest regrowth and building usage, (b) the wide range of useful wood by-products derived at multiple time points such as during forest thinning, wood product milling, and even combustible residues at the end of the building life-span, (c) the broad array of forest products involved; (d) the multiple possible substitutions e.g., cement, steel, brick, plastic; (e) the lack of data on half-lives of various products; and (f) the need for assumptions about end-of-life disposal (FAO 2016b). Many analyses aimed at estimating the cradle-to-grave impact of production and use of particular wood products also include climate implications of harvest and processing technologies, and indirect market effects of substitution. Manufacturing processes, for example, operate on a mix of fossil energy and biomass energy, a by-product derived from wood waste. Emission reductions may be achieved when energy generated from biomass displaces fossil fuel emissions (Larson et al. 2012) but these estimates rely on assumptions about available energy mix over time (Sikkema et al. 2013).

Additional data and information are necessarily required for these types of analyses which are often larger in scope that those estimating carbon storage; each additional data input brings new types of uncertainties. For example, estimating all substitution effects on a national level might require not only data on the imports and exports of wood products but also imports and exports of all alternative products. A full environmental accounting of the impacts of the production of HWP would further involve the need to capture the wide range of environmental services of forests at each life stage for human use, air quality, water quality, and biodiversity.

Assumptions about end-of-life of wood products and about use of biomass residues are primary factors in whether or not high GHG displacement can be achieved through increased HWP (FAO 2016b, Dymond 2012). When recycling and re-use are no longer options, HWP may be burned, generating energy and potentially substituting for fossil fuels, or put in landfills. Once in the landfill, anaerobic conditions may contain and store the carbon, but conditions may also lead to the production of methane gas, potentially offsetting any greenhouse gas emission reductions associated with the production of HWP. Inclusion of end-of-life pathways in HWP carbon stock calculation models is crucial, as failure to do so leads to estimates with a high degree of error (Larson et al. 2012).

In forecasting future trends, additional assumptions are required and therefore additional uncertainties are introduced such as economic assumptions associated with substitution effects. Howard et al. (2021) considered the support for foundational assumptions in these types of analyses. They considered, for example, the assumption that an increase in production of HWP leads to a corresponding increase in use of HWP and a corresponding decrease in use of concrete, steel or fossil fuel and the assumption that the same mix of products can be produced from increased harvest rates of a given area. They conclude that the literature either does not support or only partially supports these assumptions and that actualized avoided emissions from increasing production of HWP could therefore be substantially less than what is estimated in research papers. Harmon (2019) conducted a sensitivity analysis to assess the impact of assumptions about carbon storage times with product substitution and the possibility of negative feedbacks. He concluded that product substitution benefits have likely been overestimated for many scenarios, perhaps by as much as 2- to 100-fold.

There are also definitional uncertainties that make forecasting and comparisons a challenge. Analyses often assume that wood is derived from sustainably managed forests; however, the term "sustainable" can be used to describe forest management in which no more than the annual growth increment is harvested every year or to describe a forest management system in which multiple ecosystems services, including habitat preservation, freshwater production, and recreation, are provided in addition to timber harvest. Coordinated carbon accounting will depend on global certification schemes and a consistent definition of the term "sustainable" across analyses.

Finally, there is a lack of data on and knowledge of 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 construction (Hurmekoski et al. 2018). High quality global data on furniture and niche product production as well as on production and trade of mass timber, including cross-laminated timber, glue-laminated timber, parallel-strand lumber, laminated-strand lumber, laminated-veneer lumber and wood I-joists will be a key to creating strong estimates of both carbon storage in HWP and their climate mitigation potential. The true production efficiency of HWP will also need to be estimated and monitored. Production efficiency may be of particular concern for production of new product types, as well as when new technologies are introduced or where production is rapidly increasing.

Climate Mitigation Potential of Harvested Wood Products

- Global Estimates of Climate Change Mitigation Benefits of Harvested Wood Products

Global estimates of the climate change mitigation benefits of harvested wood products differ for a wide variety of reasons. They are compiled here without an attempt to untangle methodological differences or evaluate particular methodologies.

In 2014, Oliver et al. estimated that using wood substitutes could save 14 to 31 percent of global CO2 emissions and 12 to 19 percent of global fossil fuel consumption by using 34 to 100 percent of the world's sustainable wood growth. In 2019, Johnston and Radeloff estimated a much smaller but still positive contribution of carbon storage in HWP to global emissions reduction. They estimated that the global HWP pool was a net sink of 335 Mt of CO2e in 2015 and that it could grow to as much as 441 Mt of CO2e by 2030. Their estimates indicate that the carbon stored in HWP could offset substantial amounts of emissions from industrial processes, but only in some countries, and they acknowledged that their estimates of the future potential for HWP to contribute to emissions reductions depended heavily on assumptions about market conditions. Although some news headlines about this article focused on the finding that wood products mitigate less than 1 percent of global carbon emissions, it should be no surprise that any one factor can potentially offset only a very small percentage of global emissions. It is also noted that they used an accounting approach which did not account for carbon in exported or imported HWP.

In 2015, Pilli et al. estimated emissions and removals associated with HWP from 1990 to 2030 for 28 European countries, using FAOSTAT data on production of forest products and applying three future harvest scenarios. For the period 1990-2012, their results are consistent with other studies, estimating an average HWP sink of 12.0 M MT C per year (reported as −44.0 Mt CO2 yr−1) with about 10 percent of the sink in forest pools. Over future scenarios, they observed trade-offs between the amount of carbon stored in HWP versus in the forest. They conclude both that there is limited potential for additional HWP sink in the EU and that the climate change mitigation potential of HWP should be analysed in conjunction with that of forest biomass and substitution effects. In other European scenarios, the potential emissions savings by 2030 of using wood-based construction compared to conventional building materials ranges from approximately 18 000 kilotonnes CO2e to 46 000 kilotonnes CO2e (Hildebrandt et al. 2017).

Recent work by Frits Mohren, Federico Alice and Leam Martes, Department of Environmental Sciences, Wageningen University (unpublished report prepared for FAO), explored the potential of using FAOSTAT data and updated guidance from IPCC (2019) on the production approach to create time series of country-level estimates of carbon storage in paper, sawnwood, and boards & panels. Over the period 1961-2015, based on FAOSTAT data, most of the 31 countries modeled showed a gradual increase in carbon stored in HWP. The strongest increases were most often observed for carbon storage in sawnwood. Some countries showed large fluctuations in estimated carbon storage in paper. For a few countries, the amount of carbon stored in boards & panels increased at the expense of carbon storage in sawnwood. Because boards & panels have a shorter half-life than sawnwood, this pattern led to small reductions in total carbon storage in HWP over time.

Mohren et al. (unpublished) also estimated the ratio of total carbon stored in HWP to carbon stored in above ground forest biomass. This ratio can be interpreted as the intensity of forest use for domestic production combined with expected life-span of locally-consumed wood products. The ratio is small in the case of countries with a large forest area and with limited use of HWP and/or mainly short-term product use. Across the nine African countries evaluated, the average ratio was less than 1 with only South Africa greater than 2. Large ratios suggest that national forests are used for timber production, possibly in combination with production of long-lived products such as boards and panels and sawn wood. Across the nine European countries evaluated, the ratios ranged from 8.9 to 29.4 with an average ratio just over 18. Patterns for Asian and Latin American countries were more variable. In general, the ratio tended to be highest in countries where forest management had been applied for long periods of time and across most of the forest area. For a few countries, the percent of carbon stored in HWP relative to the amount of carbon in forest biomass is in the range of 25-30 percent, indicating the potential role of HWP as storage of carbon. Mohren et al. conclude that there is potential for increasing the amount of carbon in HWP by increasing the land area under sustainable forest management and increasing the use of timber in long-lived products.

Country-specific estimates of carbon storage in HWP based on FAOSTAT data and new IPCC guidance should be verified, where possible, against independent data and checked to ensure that there was not undue influence of incomplete reporting in FAOSTAT or forest area (FRA 2012) or of differing methods for estimating activity data across countries. In Mohren et al.'s approach, initialization of inherited stock of carbon in HWP was based on the average values for the first five years of production data. This approach reflects relatively new guidance from the IPCC (2019) and there is a need to explore potential biases where there are incomplete or less accurate data at the beginning of the reporting period.

Global estimates of the potential climate mitigation value of substitution of more carbon intensive products by wood products are less common. A recent overview paper estimates the mitigation potential from 2020-2050 of substitution as 0.3 – 1 Gt CO2e per year (Roe et al. 2019).

- Research Studies Evaluating Climate Change Mitigation Potential of Harvested Wood Products by Country

A large number of studies, across diverse areas and using a range of methods, have indicated that use of HWP can reduce carbon emissions at the national level in both the long and short term. Country level assessments exist for many countries where the forest product sector is large, detailed verifiable and transparent data exist, and technical capacity for quantitative work is strong.

Early studies in **Canada**, for example, found that the total carbon pool associated with the forest product sector had increased by 23.5 M MT C per year (reported as 23.5 Tg C yr^{-1}) from 1985-1991 and that the pool of carbon associated with this sector was 837 M MT C (reported as 837 Tg C) at the end of that period (Apps et al. 1999; Kurz et al. 1992). Export was a large consideration. Only 32 percent of the carbon pool had remained in Canada and although the carbon pool in HWP was small compared to that of forest ecosystems (86 000 M MT C in 1989, reported as 86 Pg), it had the potential to contribute to climate mitigation.

In the **USA**, a study by Skog (2008) estimated that the HWP contribution to removals was 30 M MT C (reported as 30 Tg C) for the production approach, 31 M MT C (reported as 31 Tg C) for the atmospheric flow approach, and 44 M MT C (reported as 44 Tg C) for the stock change approach. To put this in context, estimated carbon storage in HWP was 17-25 percent of C removals by forests, or would offset 42-61 percent of residential natural gas C emissions in 2005. The contribution was declining over time under the production and atmospheric flow approaches since 1990 but had increased under the stock change approach which includes imports. These results not only provide evidence of the potential value of HWP in climate mitigation but highlight the need to consider accounting method in evaluation of HWP emission studies. This study is one of the few to explicitly consider uncertainty in inputs. It includes a Monte-Carlo sensitivity analysis to estimate an overall 90 percent confidence interval, across all three accounting methods, for the estimate of carbon removal of –23 percent to +19 percent. Decisions about boundary conditions increase variability across study results even further. A recent study from North Carolina, **USA**, for example, estimated that, once all the factors associated with harvesting trees for production of wood products were estimated, including forgone sequestration capacity, decay of logging residuals and fertilizer, the emissions are positive and estimated at over 44 M MT (reported as 44 million metric tons) of carbon dioxide per year, making the forestry sector one of the most carbon intensive in that state (Talberth 2019).

A recent study of carbon stock change in **China** applied a production approach to estimate the carbon stock change of China's HWP from 1900 to 2016. During this period, the carbon stock of HWP grew substantially. The estimated carbon stock in use and at solid waste disposal sites was estimated at 649.2 M MT C (reported as 649.2 TgC) with solid wood products as the main source of increased carbon stocks including 346.8 M MT C (reported as 346.8 TgC) in wood-based panels and 216.7 M MT C (reported as 216.7 TgC) in sawnwood. Carbon inflow to China via imports increased substantially after the 1990s and reached 47.6 M MT C (reported as 47.6 TgC) in 2016 (Zhang et al. 2019).

The magnitude of international trade and the importance of accounting systems links HWP analyses across continents. **New Zealand** reported export of 15.5 M m3 logs, accounting for 53 percent of the national harvest, of which 96 percent is exported to China, South Korea, and India (Manley and Evison 2017). Policy implications of accounting methods for forest growers in New Zealand are therefore large. An estimation of the carbon accumulation in HWP in **Portugal** for the period 1990–2000 varied between 0.11 and 1.02 M MT C (reported as 112 and 1016 Gg C) per year depending on the accounting method applied; because Portugal is a net exporter, the atmospheric-flow approach provided the most favourable results (Dias et al. 2007).

For 2016, **Switzerland** estimated a net carbon gain of 0.016 M MT C (reported as 58 kt C). They applied the first-order decay model using default half-lives. Following the provisions of the Kyoto Protocol, they excluded HWP originating from imported wood and accounted for HWP originating from deforestation activities on the basis of instantaneous oxidation. The total inflow of carbon to the HWP pool in 2016 was estimated as 0.64 M MT C (reported as 640 kt C) (39 percent from sawnwood, 26 percent from wood-based panels, 36 percent paper and paperboard). The outflow from the pool amounted to 0.582 M MT C (reported as 582 kt C) in 2015 (43 percent from sawnwood and 23 percent from wood-based panels, 34 percent paper and paperboard) (Carmon and Rogiers 2018).

In **Sweden**, the estimated climate change mitigation potential, through substitution, of the annual production of wood products, pulp, and paper is 37.2 M MT CO2e per year from an estimated 70 million cubic meters of wood (Holmgren 2019). This estimate of the climate change mitigation potential followed the methodology of Holmgren and Kolar (2019) and some uncertainties of this approach were acknowledged, e.g. uncertainty surrounding the concept of substitution and variations between niche products. Using national data, carbon stocks in HWP were estimated to have increased for **Ireland** from 1961- 2009 mainly due to domestic harvest and increasing use of wood in long-lived products (Donlan et al. 2012).

Alice (2019) explored the carbon lifecycle balance of one hectare of tropical timberland in **Costa Rica**. He estimated that, by incorporating all lifecycle processes including forest regrowth and under sustainable forest management, the production of HWP can result in -2.19 (-5.26, 1.86) MT C (reported as -2.19 (-5.26, 1.86) Mg C) emission per hectare over one 15-year rotation. Higher harvesting intensities might lead to positive emissions. The greatest challenges he identified to maintaining the managed forest as a carbon sink were damage during logging, insufficient recovery time, and high allocations of the wood to short-lived products such as paper. Using country-specific data and a production approach including seven categories of wood product differentiated by source, he estimated that carbon storage in Costa Rica has increased from 1990 to 2016, mainly due to increased wood production. In 2016, annual storage in HWP was estimated at 30 percent of the national land-use carbon emissions and total carbon storage in HWP was estimated at 112 363 M MT C (reported as 412 Gg CO2), the vast majority of which was in solid waste disposal sites.

The considerable range in estimated carbon storage or emission reduction within and across studies results from differences in true conditions, e.g., materials being replaced, localized detail in wood product life cycles, construction types, and wood species, as well as differences in analytical conditions (many of which were discussed above), e.g. assumptions, parameters, methods, and modelling system boundaries.

- Research Studies Evaluating Climate Change Mitigation Potential of Harvested Wood Products by Product Type

In a meta-analysis of 51 studies of substitution effects for wood and wood-based products, a large majority of studies indicated that the use of wood and wood-based products was associated with lower fossil and process-based emissions when compared to non-wood products. The average substitution effect was 1.2 kg C / kg C, suggesting that, on average, for each kilogram of C in wood products that are used to substitute for non-wood products, there is an emission reduction of 1.2 kg C, with 95 percent of the values between -0.7 and 5.1 kg C / kg C. (Leskinen et al. 2018). Variability across studies resulted from product type considered, non-wood materials substituted, inclusion of particular production technologies, assumptions about end of life management practices, and model system boundary conditions.

In a second study, all wood products, including lumber, doors, I-joists, railroad ties and more, provided notable carbon emissions savings when used in place of non-wood alternatives in building construction. For example, one wooden utility pole could reduce carbon emissions by 5 618 kg CO2e (Bergman et al. 2014). The estimated displacement factors (i.e. carbon emission reduction per standardized amount of additional wood products used) varies among studies because of differences in system boundaries of the models applied, assumptions about which non-wood materials are substituted, and assumptions about the energy mix in construction materials manufactured (Sathre and O'Connor 2010; Geng et al. 2017).

Less research has been conducted on wooden furniture production in part because of the variability of products and species and also because official global data on the volume of wooden furniture production are not yet collected. Wooden furniture accounted for about 50 percent of the global furniture production in 2013 and was almost 40 percent of international furniture trade, valued at US$456 billion (FAO 2016b). The large increases in production of wood-based panels (Figure 3) has been driven by their key role in this substantial industry.

Carbon storage potential is, perhaps, greatest for wood-based construction because of the considerable quantity of wood consumed, the large quantity of raw materials being substituted, and the long expected half-life of wood in houses and buildings. Recent advances in wood technology have led to the proliferation of high-performance, engineered, wood products for structural use. The products include cross-laminated timber (CLT), glue-laminated timber (glulam), parallel-strand lumber (PSL), laminated-strand lumber (LSL), laminated-veneer lumber (LVL) and wood I-joists. The development of these products has enabled the construction of tall, multi-story wooden buildings. For example, Framework, a 12-story mixed-use tower is being built in Portland, Oregon, USA and will be the tallest human-occupied all-wooden structure in the USA. Construction of a 24-story wooden building is also underway in Vienna, Austria (Hurley 2017). Collectively known as mass timber, these products are performing well in tests against fire and earthquakes (Hurley 2017) and in assessments of their carbon footprint. Vancouver's 18-story Brock Commons tower is estimated to have offset 2 432 MT of carbon (Cecco 2019).

Mid-rise buildings, four to seven floors, may have even greater cumulative impact on climate change mitigation than high-profile, high-rise buildings because they are more numerous and thus represent a larger material flow (FAO 2016b). A meta-analysis of carbon displacement factors of wood product substitution in apartment buildings found that, on average, wood construction reduces emissions by about three times the amount of carbon in the wood products used; however, the result ranges from near parity to just above six. Carbon conversion is somewhat lower in other types of construction and estimates are similar whether the wood is being used to replace steel or concrete (Table 3; Sathre and O'Conner, 2010). In a follow-up study, Leskinen et al. (2018) estimated an average substitution effect for structural construction, e.g., walls, frames, and beams, of 1.3 kg C / kg C wood products and for non-structural construction, e.g., windows, doors, and flooring, of 1.6 kg C / kg C wood product.

For single family houses, an Australian study (Ximenes and Grant 2013) estimated that use of a "timber maximised" design could offset between 23 and 25 percent of the total operational energy of the house. In the USA, estimates of carbon storage in HWP within a wood framed house ranged from 4.6 to 6.1 MT C (reported as metric tons CO2) depending on house style and location (Lippke et al. 2004). Such building specific estimates are becoming more common. There is a relatively new project in Quebec, "Gestimat", which provides software for comparative analyses of GHG emissions associated with potential new building projects by estimating, for example, carbon storage in the foundation, beams, flooring, roofing and both interior and exterior walls. The tool is aimed at helping builders, promoters, and public authorities understand and communicate trade-offs in GHG emissions associated with alternative building designs.

Table 3: Estimates (low, middle, and high) of wood product substitution displacement factors for buildings. The displacement factor is calculated as the ratio of the change in carbon emissions for wood versus non-wood building products divided by the change in amount of wood used (also expressed as carbon). It can be understood as tC emission reduction per tC additional wood product used. Where values are presented for both the wood versus traditional (steel) columns and for the wood versus concrete columns, they represent a comparison in estimated displacement factors when wood replaced steel versus concrete (modified from Sathre and O'Connor, 2010).

Building Type	Wood vs. Traditional (Steel)			Wood vs. Concrete			Reference
	Low	Middle	High	Low	Middle	High	
Apartment building	-2.3	4.3	7.4				Börjesson and Gustavsson (2000)
Apartment building	4.4	6	7.5				Eriksson *et al.* (2007)
Apartment building (Sweden)	1.9	3.7	5.6				Gustavsson *et al.* (2006)
Apartment building (Finland)	0.4	1.8	3.3				Gustavsson *et al.* (2006)
Apartment building	0.1	2.3	7.3				Gustavsson and Sathre (2006)
Apartment Building (AVERAGE)	**0.9**	**3.62**	**6.22**				
6-storey office building (timber)	0.7	0.9	1.1	0.9	1	1	John *et al.* (2009)
6-storey office building (max wood content)	1.1	1.3	1.4	1.3	1.3	1.3	John *et al.* (2009)
3-storey building	1.5	2.3	3.1				Scharai-Rad and Welling (2002)
Warehouse	0.7	1.2	1.8				Scharai-Rad and Welling (2002)
Office building	1.1	1.2	1.2				Buchanan and Levine (1999)
Industrial building		1.6					Buchanan and Levine (1999)

Linkages between Estimating Climate Change Mitigation Potential of Harvested Wood Products and Decision-making

Estimating contributions of HWP to climate change mitigation plays a role in many decision-making processes. These include estimates for 1) country level accounting of GHG emissions and sinks under the UNFCCC, 2) forest carbon credits used in regional or national emission control policies, 3) guiding regional or local sustainable forest management, 4) environmental product declarations (EPDs), and 5) guiding development and deployment of new wood products. As above, a clearer understanding of the role of HWP in climate mitigation can also support reporting on the SDGs.

National GHG reporting to the UNFCCC calls for accurate, precise, and complete estimates of carbon storage in HWP over time and by country. The presence of these estimates in the national inventories indicates to countries that their management of wood products production can contribute to meeting their emission reduction commitments. National estimates of emissions associated with HWP may also aid countries in managing their forests. Data and estimates of carbon storage in HWP are particularly important when developing optimal strategies on how forests and the forest sector can contribute to climate change mitigation.

Documented increased carbon storage in HWP may incentivize the use of long-lived HWP to mitigate climate change (Jasinevičius et al. 2018). For example, Swiss research by Werner et al. (2010) suggests several strategies for optimizing the contributions of the forestry sector to mitigate climate change as a result of detailed investigations in carbon emissions associated with HWP. Recommendations include continuously maximizing the harvested sustainable increment while taking into account biodiversity conservation and other ecosystem services and processing the harvested wood in accordance with the principle of cascade use, using only waste wood to generate energy. They found that, globally, the effect of substitution through the material and energy use of wood is more significant and sustained as compared with the stock changes in carbon associated with HWP.

Nabuurs et al. (2017) have elaborated a strategy for "climate smart forestry" related to LULUCF reporting in the European Union including improved forest management, forest area expansion, energy substitution, and establishment of forest reserves. They estimate that the European Union could achieve an additional combined mitigation impact of 120 M MT C per year (reported as 441 megatonnes CO2/year) by 2050 through this strategy. Valuing carbon sequestration among competing environmental services is complex. Many cautiously note that maximizing forest carbon sequestration may not be compatible with, for example, biodiversity conservation.

Challenges to harnessing the climate mitigation potential of HWP include low acceptance of wood as a building material, ensuring processing efficiency, and few policy incentives to stimulate resource efficient and low carbon buildings (FAO 2016b). Relevant trends for the future of wood construction include technical advances in high performing, load-bearing wood construction; harmonization of fire protection and environmental regulations; and growth in the production capacity of ecological construction materials (Hildebrandt et al. 2017). In some countries, policies already underway. In France, for example, new policies are requiring that buildings higher than eight storeys constructed for the 2024 Paris Olympics must be made entirely of timber and, soon, all new public buildings will be constructed from at least 50 percent wood or other sustainably sourced materials (GCR 2020). In Japan, laws are being developed to promote the use of wood materials (Umeda 2010) and, in 2019, Australia extended national construction codes to increase the height of buildings in which fire-protected timber construction systems can be used (Sinclair 2019).

The global Environmental Product Declaration (EPD) system was created in accordance with the International Organization for Standardization (ISO) standard ISO 14025 (Environmental labels and declarations) as well as European engineering standards. It provides independently verified and registered documentation about the environmental impact of a product, over its life cycle. EPD has the potential to increase comparability across LCA and to allow more companies to quantify the impact of their products. EPD could be a major driver for wider implementation of life cycle data in local and national policies and building codes. On-line carbon footprint assessment tools are also available (e.g. in Canada, https://www.cecobois. com/en/calculators) which provide comparative information to support decision-making and policy development in the construction sector.

Finally, a detailed understanding of uncertainties in the estimates of the mitigation potential of HWP can reduce the risk of implementing policies with unintended consequences while also incentivizing data collection efforts that can efficiently reduce those uncertainties. Reductions in uncertainties can prevent policy-making inertia that results from information which appears too uncertain and can lead the way to more ambitious policy-making. Key questions remain. For example, the summary of an international conference, "Forests and the Climate: Manage for maximum wood production or leave the forest as a carbon sink?" outlined several unknowns, including the need to more clearly understand trade-offs between biomass production, carbon sequestration, and storage of carbon in forests and forest products as well as whether the right balance might shift across ecoregions or climate change mitigation objectives (Berndes et al. 2018).

Next Steps for Estimating Climate Change Mitigation Potential of Harvested Wood Products

Accurately and precisely estimating the climate change mitigation potential of HWP is valuable for making good decisions across a wide range of sectors and for designing strong policies. Although great progress has been made, knowledge gaps, inconsistencies, and uncertainties remain. Agencies, industry, academia, and governments will need to work together to continue moving the state of knowledge forward. The following activities are proposed for consideration as useful next steps to address the existing gaps, inconsistencies and uncertainties as well as to improve the ability to quantify the contributions of HWP in meeting the SDGs.

- Increasing the Geographic Scope of Estimates of Climate Change Mitigation Potential of Harvested Wood Products

A great deal of research and modelling has been carried out in developed and more northerly countries but much less work has been done in developing countries where there are often fewer reliable data sets, and therefore, a heavier reliance on default parameters. Such work could benefit from an improved understanding of regional differences in the climate mitigation potential of wood products and also of species differences, in particular coniferous versus non-coniferous species. The impact of whether emissions from HWP decay are counted where wood products are produced or where they are consumed requires further discussion as the choice has a strong influence on the degree to which positive climate impacts of sustainable forest management are captured by least developed countries and further on where incentives for sustainable forest management occur. In understanding substitution effects, there has been a call for more studies considering Asia, South America, and Africa as well as south and east Europe (Leskinen et al. 2018).

Estimates of trends in carbon storage in HWP, particularly for less-developed countries can provide a key source of information for tackling the above challenges. FAO compiles and makes publicly available data on production and trade of forest products over time which can be leveraged to support countries in GHG emission reporting, in sustainable forest management planning, and in developing policies to support forest-based industries.

- Accounting for Uncertainties

A better understanding of uncertainties and development of approaches for communicating and leveraging these uncertainties can support needed work on more advanced topics related to carbon storage in HWP. Birigazzia et al. (2019) propose that data collection methods, such as sampling design, be reported along with national data and provide a detailed list of questions to support such reporting. Such information could dramatically improve opportunities for a transparent accounting of uncertainties. Through uncertainty management, "a sound basis can be provided to produce more reliable estimates of the magnitude of absolute and trend uncertainties in greenhouse gas inventories than has been achieved previously. Whatever the level of complexity of the inventory, good practice provides improved understanding of how uncertainties may be managed to produce emissions estimates that are acceptable for the purposes of the UNFCCC, and for the scientific work associated with greenhouse gas inventories" (IPCC 2001). Verifiable and transparent data on traditional as well as emerging wood products are also key to reducing uncertainties.

Ideally, uncertainties resulting from default assumptions about half-lives and carbon content could be estimated using a Monte Carlo approach to provide a distribution of estimates of carbon storage in each wood product type, for any particular time period, and for any country. Certainty could then be compared and communicated in a policy-relevant manner. For example, one could describe the probability that stored carbon is greater than or less than thresholds of policy interest, the likelihood of estimated trends given uncertainty, and the value of improved national estimates in reducing uncertainty. Improving capacity to quantify carbon storage in HWP through uncertainty assessments can lead to increased activity in businesses and markets associated with the production and sale of sustainably produced wood products and also to coordinated and sustainable management of forested ecosystems.

- Expanding Analysis Frameworks to Include Emerging Forest Products

New forest products are constantly emerging. Thus, there is a need to identify the opportunities and constraints related to the development of increased forest and wood utilization, including wider product ranges and more advanced forest and wood products. Careful assessments will be required of both the environmental impacts and of the potential benefits of substituting fossil-based products with forest-based products. Assessment of the role of existing and novel forest products in the development of the global bioeconomy, including identification of case examples and gaps in knowledge will also contribute to future decision-making. In particular, there is a demand for quantification of the potential substitution benefits of novel, commercially viable forest-based products and the possibilities for these products to provide substitution benefits across a range of jurisdictions.

- Supporting a Wide Range of Analyses on the Total Impact of Producing Forest Products

A full accounting of the climate benefits and estimation of future climate benefits of forest products requires analyses across the entire life of a product (Lippke et al. 2011). Forecasts of GHG emissions associated with HWP rely on economic assumptions, detailed forecasts, and a clear understanding of the linkages between increased/decreased forest product consumption and total extent of forestland (Larson et al. 2012). In understanding and estimating potential substitution effects, much research is also needed on substitution multipliers (Nabuurs et al. 2017). Additional work on the impact of recycling on carbon emissions from wood products will be necessary. In almost all cases, a great deal remains to be understood about end-of-life pathways for HWP which can dramatically alter estimates of GHG emissions, including both CO2 and CH4, associated with HWP.

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