Substitution Estimates for Wood Products in the United States, 1990 to 2020

Adam Taylor
Elias Hurmekoski
Consuelo Brandeis
Grant Domke

Abstract

Forest carbon stock changes are routinely reported at the national level. Such accounting usually includes carbon sequestered by live trees and stored in living and dead trees, litter, and soil. The carbon stored in harvested wood products (HWPs), while in use and after disposal, may also be reported. However, wood products may provide a further indirect carbon benefit by providing an alternative to materials that require relatively large inputs of fossil-derived carbon. This "substitution impact" of HWPs is not explicitly considered in national reporting for forest carbon accounts because it is not directly comparable with absolute emissions and removals. However, the substitution impact is avoided fossil emissions, which do affect the net climate impact of wood use. Here, we estimate the total substitution impact for wood products harvested recently from forests in the United States. The total substitution impact is based on reported volumes of national wood production and the substitution factors for individual products. The substitution factors are obtained from comparative life-cycle assessments of specific wood products and their nonwood alternatives. The total substitution impact for wood products in the United States in 2020 was 188 $TgCO_2$ equivalents. Calculation of substitution factors is challenged by assumptions about the use of wood products and their alternatives and by limited availability of current and specific life-cycle assessment data; however, our findings indicate that the substitution impact of forest products are a relatively important component of the carbon benefits of wood-based products.

Forests are an important part of the carbon cycle and play a substantial role in climate-change mitigation (Griscom et al. 2017). Trees sequester and store carbon, and forests in the United States are a substantial net carbon sink. The wood in harvested trees is also capable of storing carbon for various durations while in use and after disposal in landfills. These carbon stores (expressed in terms of global warming potential, i.e., CO_2 equivalents [e]) are reported nationally for the United States (Domke et al. 2023) as part the United Nations Framework Convention on Climate Change reporting requirements (IPCC 2014).

The primary cause of climate change is the combustion of fossil fuels (Friedlingstein et al. 2022). Wood products may provide climate benefits by providing alternatives to materials whose production requires relatively large fossil fuel inputs (e.g., concrete, steel, plastics, etc.). This "substitution" effect is variously referred to as "displacement," "embodied carbon reduction," and, more recently, as "carbon handprint" (Biemer et al. 2013; Grönman et al. 2019). Carbon handprint is meant to contrast with the term "carbon footprint," which is a common reference to the fossil carbon emissions associated with a material's production and use. The substitution factor of wood products can be quantified as the reduction in fossil-based greenhouse gas emissions when using wood in place of another material, expressed per mass of the wood used (Sathre and O'Connor 2010).

Life-cycle assessment (LCA) is a standardized method to account for the holistic environmental impacts of products and processes, including their global warming potential (GWP), an indicator that is expressed as CO_2e. LCA is an

The authors are, respectively, Professor, Univ. of Tennessee, Ag Campus, Knoxville, Tennessee (AdamTaylor@utk.edu [corresponding author]); Academy Research Fellow, Dept. of Forest Sci., Helsinki Inst. of Sustainability Sci., Univ. of Helsinki, Helsinki, Finland (elias.hurmekoski@helsinki.fi); Research Forester, USDA Forest Serv. Southern Research Sta., Forest Inventory and Analysis (consuelo.brandeis@usda.gov); Research Forester, USDA Forest Serv. Northern Research Sta. (grant.m.domke@usda.gov). This paper was received for publication in June 2023. Article no. 23-00036.

Forest Prod. J. 73(4):362–369.
doi:10.13073/FPJ-D-23-00036

active area of research and has produced GWP estimates for many products. The substitution of materials requiring greater fossil-fuel inputs with lower-carbon materials such as wood-based products results in a reduction in greenhouse gas emissions. Substitution factors for wood products have been calculated by comparing the LCA GWP data of wood products and their alternatives. The calculation of wood products substitution factors is difficult because of, e.g., variations in LCA methods and assumptions, regional differences, and uncertainties regarding the functional equivalence of wood products and alternatives. Despite this uncertainty, reviews of the literature generally support the concept that using wood in place of other materials results in lower fossil GWP; thus there is a substitution carbon benefit or a positive fossil carbon handprint for wood products (Sathre and O'Connor 2010; Leskinen et al. 2018; Hurmekoski et al. 2021). These assessments are based on fossil emissions only and should exclude consideration of biogenic carbon stock changes (i.e., changes in forest carbon stocks) to avoid double counting and noncounting of emissions. Therefore, substitution impact or handprint does not equal the climate change mitigation potential of wood products, but it does provide one component of the overall climate impact of wood use.

The concept of climate-smart forestry explicitly recognizes the contribution of wood product substitution to wood's climate mitigation benefits, in addition to the carbon stored in forests and harvested products (Nabuurs et al. 2017). Despite the general recognition that wood can provide substitution benefits and that these benefits can be included in analysis of forest carbon dynamics (McKinley et al. 2011; Pukkala 2018; Hurmekoski et al. 2020), there has been minimal reporting of the magnitude of the overall substitution impacts of wood production—partly due to the difficulty of interpreting such values. Hurmekoski et al. (2023) reported the substitution impact of the current array of wood-based materials produced in Finland to be over 12.5 $TgCO_2e$ (10^{12} g = megaton) per year. To provide perspective, the total annual sector-wide greenhouse gas emissions for Finland are approximately 48 $TgCO_2e$ (Ministry of the Environment [Finland] 2022).

To the best of our knowledge, there is no estimate for nationwide substitution impacts of wood products produced in the United States. Thus, the purpose of this study was to quantify the substitution impact of wood products in the United States in the recent past, as well as to discuss the interpretations of such impacts relative to greenhouse gas (GHG) accounting and climate-change mitigation analyses.

Materials and Methods

The mass of stored biogenic carbon (in metric tonnes, i.e., tC) contained in a reported product volume (m^3) or mass (t) was multiplied by its product-specific substitution factor (tC/tC) to yield that product's substitution impact (converted to tCO_2; Hurmekoski, et al. 2023). The sum of the substitution impacts for the full array of products was used to estimate the total substitution impact, expressed as $TgCO_2e$.

United States' wood production

Wood production estimates are compiled and reported by the US Department of Agriculture Forest Service to the United Nations (FAOSTAT 2023), with total production volumes reported for 1990, 1995, 2000, 2005, 2010, 2015, and 2020. Carbon content of various products was taken from the International Panel on Climate Change (IPCC) guidelines (IPCC 2019). Carbon mass was converted to CO_2e by multiplying by 3.67, the ratio of the molecular weights of carbon and carbon dioxide.

Allocation to various end uses within each wood product category was collected from various sources as described below. Data used were from the 2020 reporting year or the most recent year available. Allocations were assumed to be the same in all previous years.

Substitution factors

Substitution factors were calculated as the GWP differential relative to the difference in biogenic carbon content of the materials being compared. This is the same as the calculation done by Sathre and O'Connor (2010), who referred to the product as "displacement factor":

$$\text{Displacement factor} = \frac{GWP_{\text{nonwood option}} - GWP_{\text{wood option}}}{C_{\text{wood option}} - C_{\text{nonwood option}}}$$

Substitution factors were calculated for wood options compared with their alternative material, or with the market-share-weighted average of their options, in some cases where we identified more than one option. Data were taken from the most recent LCA studies or environmental product declarations (EPD) conducted in the United States, as available. Exceptions are noted below. These data included consideration of assumed differences in the service life of the wood and nonwood options. Biogenic carbon was excluded and life-cycle stages from cradle to gate (stage A in International Organization for Standardization [ISO] standard 21930 [ISO 2017]) or cradle to grave (stages A–C in ISO standard 21930 [ISO 2017]) were included depending on data availability. The identification of the substitute products is the most important yet the most uncertain assumption. Following previous literature (e.g., Rüter et al. 2016), we selected substitute products on the basis of expert judgment trying to ensure functional equivalence between the substituted services. Specifics for the various wood products and assumptions regarding their alternatives are described below; the resulting substitution factors are listed in Table 1.

Primary construction

The greatest use of wood in the United States is for primary construction. Proportions of sawn wood (coniferous and nonconiferous) allocated to construction and other uses was assumed to be as reported by Howard et al. (2017) for 2017. Proportions of plywood and oriented strand board (OSB) allocated to various uses was as reported by APA—The Engineered Wood Association (2022) for the year 2020. A small amount of primary construction application of nonstructural panels (for molding and millwork) was reported by the Composite Panel Association (2023).

An average end-use substitution factor was applied to all primary construction uses on the basis of a whole-building LCA comparison of a wood-framed and a steel-framed house in the United States (Lippke et al. 2004). In that study, there were many wooden components common to each house option; the differences in the whole buildings' embodied fossil carbon were due to alternative materials used in the walls and floors. For this analysis, the same substitution factor

Table 1.—End use, volume, and estimated substitution impacts of wood products harvested from forests in the United States in 2020.

Category	End use	Alternative material(s)	Proportion of category	End-use substitution factor (tCO_2e/tCO_2e)	Weighted-average substitution factor (tCO_2e/tCO_2e)	Production volume (TgC)	Impact ($TgCO_2e$)
	End uses within each category				Category-wide		
Solid wood products							
Coniferous sawn wood	Primary construction	Steel	70%	0.96	1.11	14.21	57.63
	Packaging (pallets)	Plastic	9%	0.34			
	Other (including furniture)	Steel shelving	3%	0.36			
	Treated industrial	Steel, concrete, fiberglass	3%	1.40			
	Treated decking, fencing	Wood–plastic composite	15%	2.39			
Industrial coniferous roundwood	Treated posts, poles, and pilings	Steel, concrete, fiberglass	100%	1.40	1.40	1.66	8.52
Nonconiferous sawn wood	Primary construction	Steel	15%	0.96	0.60	4.40	9.66
	Flooring (solid)	Ceramic tile, luxury vinyl tile, and vinyl sheet	6%	1.59			
	Flooring (laminate)		4%	0.99			
	Packaging (pallets)	Plastic	44%	0.34			
	Other (including furniture)	Steel shelving	20%	0.36			
	Ties and timbers	Concrete	12%	1.23			
Plywood and veneer	Primary construction	Steel	66%	0.96	0.75	2.72	7.47
	Packaging (pallets)	Plastic	19%	0.34			
	Other (including furniture)	Steel shelving	15%	0.36			
Oriented strand board	Primary construction	Steel	87%	0.96	0.75	2.58	8.34
	Packaging (pallets)	Plastic	5%	0.34			
	Other (including furniture)	Steel shelving	8%	0.36			
Particleboard	Primary construction	Steel	2%	0.96	0.37	1.34	1.82
	Furniture and fixtures	Steel shelving	98%	0.36			
Medium-density fiberboard	Primary construction	Steel	22%	0.96	0.62	0.80	1.81
	Flooring (laminate)	Ceramic tile, luxury vinyl tile, and vinyl sheet	20%	0.99			
	Furniture and fixtures	Steel shelving	58%	0.36			
Hardboard	Other (including furniture)	Steel shelving	100%	0.36	0.36	2.27	2.97
Insulation board	Insulation	Glass wool, rockwool, polystyrene	100%	−0.20	−0.20	0.41	−0.29
Pulp and paper							
Dissolving pulp	Textiles (viscose)	Cotton, polyethylene	63%	0.88	0.55	0.44	0.90
	Plastics, films, cigarette filters	N/A	37%	0.00			
Mechanical pulp	Packaging papers	Plastic	70%	1.12	0.78	1.92	5.51
	Graphic and tissue paper	N/A	30%	0.00			
Chemical pulp	Packaging papers	Plastic	70%	1.12	0.78	18.83	54.20
	Graphic and tissue paper	N/A	30%	0.00			
Energy							
Energy wood	Commercial heating	Fossil fuel mix	4%	0.68	0.23	13.90	11.90
	Electrical power generation		9%	0.68			
	Household heating		21%	0.68			
	Industrial (including wood manufacturing)	N/A	66%	0.00			
Pellets	Household heating and electrical power generation	Fossil fuel mix	100%	0.68	0.68	4.08	10.17
Solid waste incineration	Industrial heat and power		100%	0.68	0.68	2.78	6.93
US sum of substitution impacts for 2020							188 $TgCO_2e$

(wood in place of steel) was assumed to apply to all the wood used (e.g., lumber and panels used in roofing).

Poles

Poles are a component of the coniferous roundwood category that are preservative treated and used for industrial applications. Production volumes were taken from Vlosky (2009) for poles and pilings, which are the most recent data available. The displacement factor was calculated from a recent comparative LCA of treated wooden poles versus steel, concrete, and fiberglass alternatives (Bolin and Smith, unpublished data). The displacement factor was weighted by the estimated market share of the alternatives (Osmose [no date]).

Treated sawn wood

Volumes of treated decking, boards (e.g., fencing), and landscape timbers were taken from Vlosky (2009). Bolin and Smith (unpublished data) provided comparative LCA data of treated decking lumber versus a wood–plastic composite (WPC) alternative, from which the displacement factor was calculated. Treated dimensional lumber was excluded from consideration in this category because although it is produced in large volumes, it is unlikely to be substituted by WPC.

Pallets

Wooden pallet GWP data were taken from a recent LCA (Alanya-Rosenbaum et al. 2021) and compared with data for plastic pallets manufactured in the United States (Anil et al. 2020), with a normalization for service life as reported by Deviatkin and Horttanainen (2020).

Sawn wood (coniferous and nonconiferous [2017 production data]), plywood, and OSB (2020 production data) all contribute to pallets, as reported by the US Forest Service and by APA—The Engineered Wood Association (2022).

Furniture

Sawn wood (hardwood and softwood) and panels (structural and nonstructural) all contribute to furniture products to some extent, as reported by the US Forest Service (Howard et al. 2017) and by the panel industries (APA 2022; Composite Panel Association 2023). A single displacement factor for all wood allocated to furniture was assumed from Rüter et al. (2016), which was based on a comparison of wooden and steel shelving. The average of the 2010 and 2030 projected values was used, corrected to provide units of tC/tC.

Hardwood end uses

Nonconiferous sawn wood was allocated to products (including flooring and pallets [“packaging and shipping”]) according to 2017 data reported by the US Forest Service (Howard et al. 2017), with the exception that the “other” category (11%) was replaced by ties, which corresponds to the data provided by the Railway Tie Association for 2020 (Railway Tie Association 2023). A substitution factor for wood crossties was calculated from a comparative LCA with a concrete alternative (Bolin and Smith 2013).

Flooring

Industry average EPDs were used for major smooth floor options: hardwood flooring, engineered flooring (laminate), ceramic, luxury vinyl tile, and vinyl sheet (Resilient Floor Covering Institute 2019a, 2019b; Tile Council of North America 2020; Decorative Hardwoods Association 2022; National Wood Flooring Association 2022). Cradle-to-grave (landfill option) values of GWP were normalized to an equivalent service life (75 yr) and weighted by the 2020 market share (area) as reported by Floor Covering Weekly (2021). Carpet was excluded (even though it is almost half the market) because its GWP is extremely high, and smooth wood options might not provide a functional alternative to carpet.

Insulation board

The production of “fiberboard, other” was assumed to be for insulation board in place of glass wool, rockwool, and polystyrene, with a displacement factor as reported by Ruter et al. (2016). The average of the 2010 and 2030 projected values was used, corrected to provide units of tC/tC.

Pulp for paper

Chemical and mechanical pulp production were both allocated to packaging and nonpackaging categories in proportion to paper production values reported to the United Nations (UN; FAOSTAT 2023). A single “packaging paper” displacement factor was calculated on the basis of data from a comparative LCA of cardboard and reusable plastic shipping containers for food products (Thorbecke et al. 2019). The displacement factor was calculated for the market-weighted averages of the displacement scenarios for different product types, expressed per mass of virgin pulp fiber in the cardboard boxes. A substitution factor of zero was assumed for nonpackaging papers (e.g., tissue and newsprint) and for recovered pulp fiber. That is, communication papers were assumed to substitute for electronic media and hygiene papers were assumed to substitute for water (treatment), but the GWP difference in both cases is challenging to quantify.

Dissolving pulp

Shen et al. (2010) provide GWP values for various fibers, including viscose manufactured in various locations, polyethylene, and cotton. Because cotton and polyethylene dominate the fiber market (Textile Exchange 2022), these materials were used as the alternative, with GWP impacts weighted by global production levels. The GWP impact of the viscose option was weighted 65% to the “Asia” option (Shen et al. 2010) on the basis of the assumption that the majority of viscose production is in China (Research in China 2023). The carbon content of viscose was calculated as 44% on the basis of the assumption that it is pure cellulose. A substitution factor of zero was assumed for other uses of dissolving pulp (37% of the total; Shen et al. 2010), which include plastics, films, and cigarette filters.

Energy wood

Wood production for energy was taken from the data reported to the UN (FAOSTAT 2023). Pellet production was only reported for the 2018-through-2020 reporting periods and was assumed to be zero before that. Wood energy end-use proportions for 2020 were obtained from the US Energy Information Administration (EIA; 2023) and applied equally across all time periods. Wood and paper waste incineration for energy was calculated with data from the US Environmental Protection Agency (EPA) for 1960 through 2018 (2022b); the data point for 1995 was the average of the

Table 2.—Total substitution impact and average substitution factors of wood harvested in the United States by year.

	1990	1995	2000	2005	2010	2015	2020
Total substitution impact							
$TgCO_2e$	176	171	177	181	137	165	188
Total roundwood harvest							
$m^3 \times 10^6$	509	470	467	467	377	399	430
Weighted average substitution factor of products							
tC/tC	0.62	0.63	0.65	0.68	0.66	0.70	0.71
Substitution factor of all harvested roundwood							
tC/tC	0.41	0.43	0.45	0.46	0.43	0.49	0.52
tCO_2e/m^3	0.35	0.36	0.38	0.39	0.36	0.41	0.44

values for 1990 and 2000, and the data were assumed to be the same in 2019 and 2020 as they were in 2018. The substitution factor of wood energy sources chosen was 0.68, the midpoint of the range reported for Canada (Smyth et al. 2017), where the energy supply is heavily dependent on fossil fuels, as is the case in the United States. Wood energy used in mill operations was given a substitution factor of zero because it was assumed to be accounted for in the substitution factors of the mill's products. Similarly, energy recovery from pulp waste was assumed to be used internally and thus provides no separate energy substitution impact.

Results and Discussion

The total substitution impact of wood products was 188 $TgCO_2e$ in 2020 (Table 1). Note that this is based on a comparison of single cases covering a fraction of all end uses and functional units. Thus, the estimate only aims to explore the approximate scale of the substitution and it should be interpreted with caution. Moreover, substitution impacts are not directly comparable with absolute emissions and removals because the comparison point (i.e., the baseline scenario) is different. For example: for harvested wood product (HWP) emissions and removals, the baseline is the stock in the last time period. However, for substitution, it is the market condition that would have prevailed if wood had not been used (i.e., zero harvest). However, to help put these impacts for substitution (137 to 188 $TgCO_2e$/yr) into perspective, they represent avoided emissions equivalents to about 2% to 4% of total GHG emissions from the United States over the years evaluated here (approximately 6,000 to 7,500 $TgCO_2e$/yr; EPA 2022a).

The most important uses of wood by volume in the United States are for construction lumber in primary construction and for pulp for packaging papers (e.g., cardboard boxes). These two uses also have a dominating influence on the total substitution factors of wood products harvested, given their relatively high substitution factors (0.96 and 1.12 tC/tC, respectively) and large production volumes (Table 1). These substitution values are derived from single case studies, causing notable uncertainty. Future studies incorporating a larger number of cases for these two major wood uses may thus change the overall estimate, perhaps considerably so.

Total substitution impact varied over time because of changes in the volume and types of wood products (Table 2). The relatively low total impact in 2010 reflects reduced construction activity associated with the global economic crisis around 2008, and therefore fewer substitution opportunities for wood materials. Total substitution impacts over time have increased in part because of reduced demand for writing paper and newsprint and an increase in demand for packaging paper (Latta et al. 2016). The portion of paper production for packaging in the United States increased from 52% in 1990 to 70% in 2020 (FAOSTAT 2023) and this has contributed to an increase in the weighted average substitution factor for wood products during that time (from 0.62 to 0.71 tC/tC; Table 2).

Overall, the weighted average substitution factor—for products that were assumed to have a substitution benefit—was 0.71 tC displaced per tC in the wood product in 2020. When expressed in terms of the total wood harvest, the average substitution factor was 0.52. These factors are comparable with the average substitution factors reported in recent reviews (e.g., 0.55 in Hurmekoski et al. 2021). When expressed in terms of units of roundwood volume harvested, the fossil carbon emissions avoided is 440 $kgCO_2e/m^3$.

The substitution impacts for paper products used in this study were, on average, higher than with those used by Hurmekoski et al. (2023) for Finland. This is primarily because the end use of pulp products in the United States is relatively more in packaging (which has a high assumed substitution factor) than in tissue and graphic papers (which are assumed to have no substitution factor). If the United States' estimates had been compiled with the end-use distribution of the pulp and paper products produced in Finland, the overall impacts would be reduced to about 117 $TgCO_2e$ for 2020, about 43% lower. In contrast, the substitution factors used recently for a study in Sweden, a country with forests and forest industry similar to Finland (Skytt et al. 2021), were relatively high compared with those used in the United States' analysis. If the Sweden substitution factors were applied to the United States' production estimates for 2020, the estimated total impact would be approximately 34% higher. This range in impact estimates highlights the uncertainty created by adopting LCA case studies for individual products to generalize the results for an entire heterogeneous market.

Landfill was the only end-of-life scenario included in this analysis, and only the reported wood and paper component of solid waste that is incinerated to provide energy was included. In Finland, almost all wood and paper products are collected at disposal and incinerated for energy production, thus providing a substantial additional substitution impact (by displacing need for fossil fuels); Hurmekoski et al. (2023) found that end-of-life practice in Finland increased the total substitution impact by almost 50%. In the United States, most of the wood and paper that is disposed of ends up in landfills and provides no substitution benefit. However, the wood and paper disposed of in landfills is included in

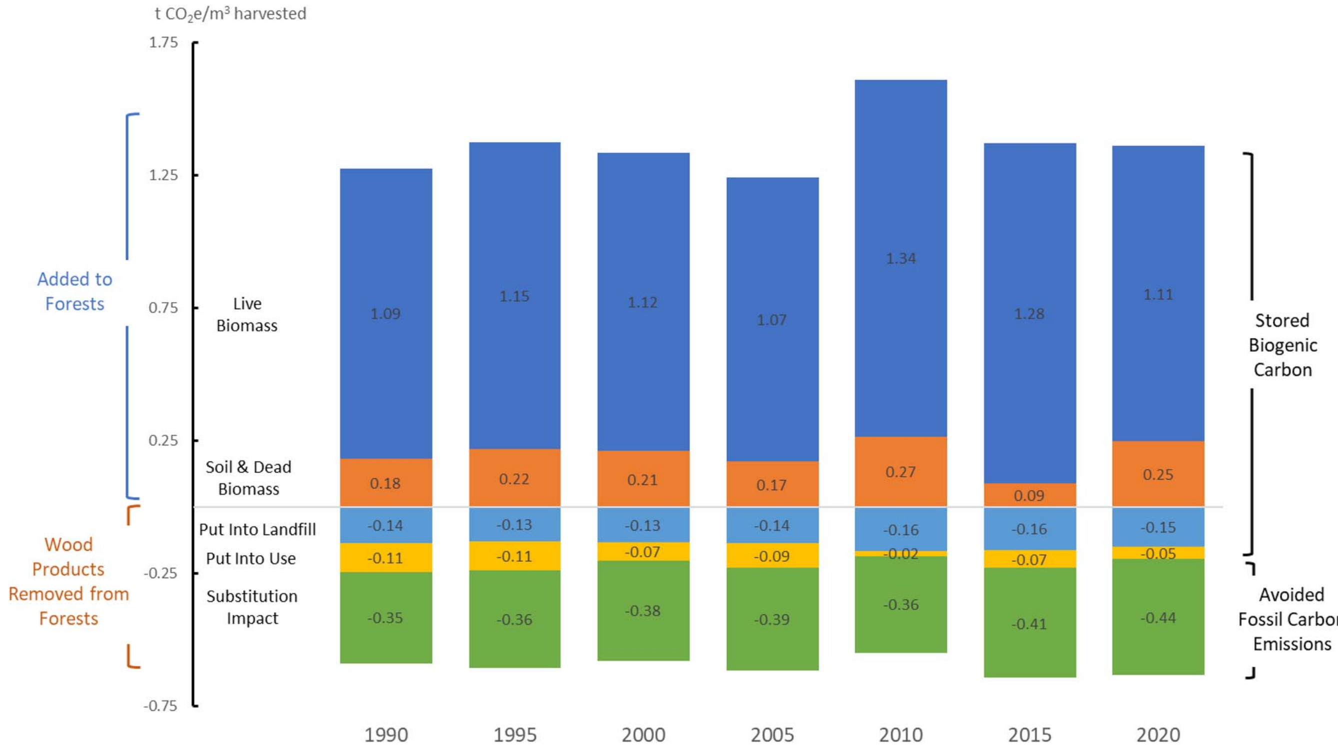

Figure 1.—Carbon storage and substitution impact (avoided carbon emissions) of forests and wood products in the United States, expressed per unit of wood harvest in various years.

calculations of carbon storage and this represents a large carbon sink in the United States: 63.6 $TgCO_2e$ in 2020 (Domke et al. 2023). As the assumed substitution factor used here for combustion of this wood and paper is 0.68 tC/tC (i.e., <1.0), then the reported carbon storage estimate may be greater than its potential substitution benefit if it were combusted for energy. This assumes that much of the wood (77%) and paper (44%) disposed of in landfills does not decay and thus represents "permanent" carbon storage (EPA 2022b).

Substitution factors are highly uncertain and contentious (Harmon 2019; Leturcq 2020). Uncertainty results in general from the lack of representative LCA case studies across the thousands of end uses, poor understanding of market dynamics, and the hypothetical nature of the exercise—trying to judge how consumer needs would have been satisfied in the absence of wood-based products. For example, the substitution factor calculation used here assumes that wood-based products substitute nonwood products at a rate of 1:1 and compares attributional LCA studies of products' average emissions. However, if the substitution were only partial, the overall impact would be reduced because the additional supply would substitute only part of the other product, with the remainder merely adding to overall supply (e.g., Chalmers et al. 2015). In addition, the products added to or removed from the market could have different emissions than the average for those products. Consequential LCA would be required to explore the impact of marginal changes in product use in response to carbon taxes or other incentives. Also, substitution factors are likely to change in the future (e.g., with the development of new products and processes and with changes in the fossil-fuel intensity of the systems that power the production of alternative materials; Brunet-Navarro, et al. 2021). Thus, this analysis only intends to explore the approximate scale of the substitution effects. Future estimations would benefit from further LCA case studies to increase the coverage of end uses as well as an analysis on market dynamics regarding which nonwood products the wood products substitute for and the direct and indirect consequences of this substitution.

A finding of substantial substitution benefits for forest products in the status quo does not necessarily imply that greater harvest levels would yield proportional carbon benefits. Hurmekoski et al. (2020) observed that increased harvest levels in Finland would result in a proportionately higher reduction in the forest carbon sink that would require products with extremely high substitution factors to offset. This may be different in the United States, having different forest ecosystems and forest product portfolios (Zhang et al. 2023).

Given that the unit change in forest (biogenic) carbon storage is greater than the sum of unit change in wood (biogenic) product storage and avoided (fossil) emissions, increased harvest levels would likely result in a net emission of carbon, at least in the short to medium term (Fig. 1). However, just as there is uncertainty regarding the amount and future potential for substitution impacts of HWPs, there is also uncertainty regarding the capacity of forests to continue to sequester and store carbon at recent rates. After a period of large-scale disturbance, during which forests in the United States represented a major source of carbon emissions, forest growth has rebounded over the past half century, in large part because of fossil fuel substitution for energy sources previously provided by wood (Birdsey et al. 2006). However, it now appears that the future carbon sequestration capacity of United States' forests is slowing. For example, Zhu et al. (2018) calculated that United States' forests are at about 80% of their storage potential, similar to much of the global forest resource (Roebroek et al. 2023). Thus, the interpretation of the balance between fossil and biogenic emissions and removals over time is not straightforward. Further research on the relationship of forest carbon stocks, HWP carbon pools, and wood product substitution factors is needed for the United States' context to judge the overall climate-change mitigation potential of wood-based products.

Conclusion

The substitution impacts of wood products from forests in the United States ranged from 137 to 188 $TgCO_2e$ annually over the past 2 decades. This is an amount equal to about 2% to 4% of total GWP emissions from the United States during that time. This large estimated impact does not necessarily imply that more HWPs would increase the net carbon benefit; associated forest carbon storage levels would need to be considered. Substitution impact estimates are very sensitive to the substitution factor used. For example, the total substitution impact estimate would have been much lower or higher if the factors used in recent studies in Finland or Sweden, respectively, has been used instead. Estimation of substitution effects involves much uncertainty because of the importance of underlying assumptions and the limited availability of LCA data. Further work to address this uncertainty would help in evaluating the overall climate-change mitigation potential of wood use in the United States.

Acknowledgments

We are grateful for the support provided by a Fulbright-Saastamoinen Foundation Grant in Health and Environmental Sciences and the University of Eastern Finland.

Literature Cited

Alanya-Rosenbaum, S., R. Bergman, and B. Gething. 2021. Assessing the life-cycle environmental impacts of the wood pallet sector in the United States. *J. Clean. Prod*. 320:128726.

Anil, S. K., J. Ma, G. E. Kremer, C. D. Ray, and S. M. Shahidi. 2020. Life cycle assessment comparison of wooden and plastic pallets in the grocery industry. *J. Ind. Ecol*. 24(4):871–886.

APA–The Engineered Wood Association. 2022. Structural Panel & Engineered Wood Yearbook. APA Economics Report E187. APA-The Engineered Wood Association, Tacoma, Washington.

Biemer, J., W. Dixon, and N. Blackburn. 2013. Our environmental handprint: The good we do. *In*: 1st IEEE Conference on Technologies for Sustainability (SusTech), 2013, Portland, Oregon, pp. 146–153.

Birdsey, R., K. Pregitzer, and A. Lucier. 2006. Forest carbon management in the United States: 1600–2100. *J. Environ. Qual*. 35(4):1461–1469.

Bolin, C. A. and S. T. Smith. 2013. Life cycle assessment of creosote-treated wooden railroad crossties in the US with comparisons to concrete and plastic composite railroad crossties. *J. Transp. Technol.* 3(2):149–161.

Brunet-Navarro, P., H. Jochheim, G. Cardellini, K. Richter, and B. Muys. 2021. Climate mitigation by energy and material substitution of wood products has an expiry date. *J. Clean. Prod*. 303:127026.

Chalmers, N. G., M. Brander, and C. Revoredo-Giha. 2015. The implications of empirical and 1:1 substitution ratios for consequential LCA: using a 1% tax on whole milk as an illustrative example. *Int. J. Life Cycle Assess*. 20:1268–1276.

Composite Panel Association. 2023. North American shipments and downstream market report. (Available to members only). https://www.compositepanel.org/resources/industry-reports/annual-shipments-and-downstream-market-report-html/. Accessed March 10, 2023.

Decorative Hardwoods Association. 2022. Cradle-to-grave EPD for industry average engineered wood flooring products. Declaration EPD 392. ASTM International, West Conshoshocken, Pennsylvania.

Deviatkin, I. and M. Horttanainen. 2020. Carbon footprint of an EUR-sized wooden and a plastic pallet. *E3S Web Conf.* 158:03001.

Domke, G., B. Walters, D. Nowak, E. Greenfield, J. Smith, M. Nichols, S. Ogle, J. Coulston, and T. Wirth. 2023. Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990–2020. Resource Update FS–382. US Dept. of Agriculture, Forest Serv., Northern Research Sta., Madison, Wisconsin, 10 p. https://doi.org/10.2737/FS-RU-382. Accessed February 15, 2023.

Floor Covering Weekly. 2021. Floor covering's rocky year. Floor Covering Weekly, New York, Vol, 70, pp. 10–12.

Food and Agriculture Organization of the United Nations Statistics (FAOSTAT). 2023. Forestry production and trade. Food and Agriculture Organization of the United Nations, New York. https://www.fao.org/faostat/en/#data/FO. Accessed March 13, 2023.

Friedlingstein, P., M. O'Sullivan, M. W. Jones, R. M. Andrew, L. Gregor, J. Hauck, C. Le Quéré, I. T. Luijkx, A. Olsen, G. P. Peters, W. Peters, J. Pongratz, C. Schwingshackl, S. Sitch, J. G. Canadell, P. Ciais, R. B. Jackson, S. R. Alin, R. Alkama, A. Arneth, V. K. Arora, N. R. Bates, M. Becker, N. Bellouin, H. C. Bittig, L. Bopp, F. Chevallier, L. P. Chini, M. Cronin, W. Evans, S. Falk, R. A. Feely, T. Gasser, M. Gehlen, T. Gkritzalis, L. Gloege, G. Grassi, N. Gruber, Ö. Gürses, I. Harris, M. Hefner, R. A. Houghton, G. C. Hurtt, Y. Iida, T. Ilyina, A. K. Jain, A. Jersild, K. Kadono, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J. I. Korsbakken, P. Landschützer, N. Lefèvre, K. Lindsay, J. Liu, Z. Liu, G. Marland, N. Mayot, M. J. McGrath, N. Metzl, N. M. Monacci, D. R. Munro, S. I. Nakaoka, Y. Niwa, K. O'Brien, T. Ono, P. I. Palmer, N. Pan, D. Pierrot, K. Pocock, B. Poulter, L. Resplandy, E. Robertson, C. Rödenbeck, C. Rodriguez, T. M. Rosan, J. Schwinger, R. Séférian, J. D. Shutler, I. Skjelvan, T. Steinhoff, Q. Sun, A. J. Sutton, C. Sweeney, S. Takao, T. Tanhua, P. P. Tans, X. Tian, H. Tian, B. Tilbrook, H. Tsujino, F. Tubiello, G. R. van der Werf, A. P. Walker, R. Wanninkhof, C. Whitehead, A. Willstrand Wranne, R. Wright, W. Yuan, C. Yue, X. Yue, S. Zaehle, J. Zeng, and B. Zheng. 2022. Global carbon budget 2022. *Earth Syst. Sci. Data* 14(11):4811–4900.

Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, W. H. Schlesinger, D. Shoch, J. V. Siikamäki, and P. Smith. 2017. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* 114(44):11645–11650.

Grönman, K., T. Pajula, J. Sillman, M. Leino, S. Vatanen, H. Kasurinen, A. Soininen, and R. Soukka. 2019. Carbon handprint—An approach to assess the positive climate impacts of products demonstrated via renewable diesel case. *J. Clean. Prod.* 206:1059–1072.

Harmon, M. E. 2019. Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions. *Environ. Res. Lett.* 14(6):065008.

Howard, J. L., D. B. McKeever, and S. Liang. 2017. United States Forest Products Annual Market Review and Prospects, 2013–2017. Forest Products Laboratory Research Note FPL-RN-0348, Madison, Wisconsin, 11 pp.

Hurmekoski, E., J. Kunttu, T. Heinonen, T. Pukkala, and H. Peltola. 2023. Does expanding wood use in construction and textile markets contribute to climate change mitigation? *Renew, Sustain, Energy Rev*, 174:113152.

Hurmekoski, E., T. Myllyviita, J. Seppälä, T. Heinonen, A. Kilpeläinen, T. Pukkala, T. Mattila, L. Hetemäki, A. Asikainen, and H. Peltola. 2020. Impact of structural changes in wood-using industries on net carbon emissions in Finland. *J. Ind. Ecol*. 24(4):899–912.

Hurmekoski, E., C. E. Smyth, T. Stern, P. J. Verkerk, and R. Asada. 2021. Substitution impacts of wood use at the market level: A systematic review. *Environ. Res. Lett.* 16(12):123004.

IPCC (International Panel on Climate Change). 2014. International Panel on Climate Change Decision 24/CP.19 Revision of the UNFCCC reporting guidelines on annual inventories for Parties included in Annex I to the Convention http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2. Accessed May 25, 2023.

IPCC (International Panel on Climate Change). 2019. International Panel on Climate Change 2019 Refinement to the 2006 IPCC Guidelines for

National Greenhouse Gas Inventories https://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_01_Overview.pdf. Accessed July 6, 2023.
ISO. (International Organization for Standardization) 2017. International Standard ISO 21930:2017 Sustainability in buildings and civil engineering works—Core rules for environmental product declarations of construction products and services. ISO, Geneva, Switzerland.
Latta, G. S., A. J. Plantiga, and M. R. Sloggy. 2016. The effects of internet use on global demand for paper products. *J. Forestry* 114(4):433–440.
Leskinen, P., G. Cardellini, S. González-García, E. Hurmekoski, R. Sathre, J. Seppälä, C. Smyth, T. Stern, and P. J. Verkerk. 2018. Substitution effects of wood-based products in climate change mitigation. From Science to Policy 7. European Forest Institute. https://doi.org/10.36333/fs07
Leturcq, P. 2020. GHG displacement factors of harvested wood products: The myth of substitution. Sci. Rep. 10(1):20752.
Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. *Forest Prod. J*. 54(6):8–19.
McKinley, D. C., M. G. Ryan, R. A. Birdsey, C. P. Giardina, M. E. Harmon, L. S. Heath, R. A. Houghton, R. B. Jackson, J. F. Morrison, and B. C. Murray. 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecol. Appl. 21(6):1902–1924.
Ministry of the Environment (Finland). 2022. Annual Climate Report 2022. https://ym.fi/en/annual-climate-report. Accessed April 26, 2023.
Nabuurs, G.-J., P. Delacote, D. Ellison, M. Hanewinkel, L. Hetemäki, and M. Lindner. 2017. By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry. *Forests* 8(12):484.
National Wood Flooring Association. 2022. Cradle-to-grave EPD for industry average solid wood flooring products. Declaration EPD 393. ASTM International, West Conshoshocken, Pennsylvania.
Osmose. n.d. Best practices in wood pole plant management: Industry survey results. Undated report. 27 pp.
Pukkala, T. 2018. Carbon forestry is surprising. *Forest Ecosyst*. 5:1–11.
Railway Tie Association. 2023. RTA Purchases Report Data. https://www.rta.org/assets/PurchaseReports-ScenarioPlanners/2023/23-1-Purchases%20Report%20data%20202301.xlsx. Accessed March 14, 2023.
Research in China. 2023. Global and China Viscose Fiber Industry Report, 2019–2025. http://www.researchinchina.com/Htmls/Report/2019/11559.html. Accessed May 6, 2023.
Resilient Floor Covering Institute. 2019a. Heterogeneous vinyl flooring industry-wide environmental product declaration. Declaration 4788753451.101.1. UL Environment, Northbrook, Illinois.
Resilient Floor Covering Institute. 2019b. Vinyl tile industry-wide environmental product declaration. Declaration 4788753451.106.1. UL Environment, Northbrook, Illinois.
Roebroek, C., G. Duveiller, S. Seneviratne, E. Davin, and A. Cescatti. 2023. Releasing global forests from management: How much more carbon could be stored? *Science* 380(6646):749–753.
Ruter, S., F. Werner, N. Forsell, C. Prins, E. Vial, and A.-L. Levet. 2016. ClimWood2030—Climate benefits of material substitution by forest biomass and harvested wood products: Perspective 2030. Final report, Thünen Report, No. 42, ISBN 978-3-86576-160-6, Johann Heinrich von Thünen-Institut, Braunschweig. https://nbn-resolving.de/urn:nbn:de:gbv:253-201607-dn056927-3. Accessed March 2, 2023.
Sathre, R. and J. O'Connor. 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Pol*. 13(2):104–114.
Shen, L., E. Worrell, and M. K. Patel. 2010. Environmental impact assessment of man-made cellulose fibres. *Resour. Conserv. Recycl*. 55(2):260–274.
Skytt, T., G. Englund, and B.-G. Jonsson. 2021. Climate mitigation forestry—Temporal trade-offs. *Environ. Res. Lett.* 16(11):114037.
Smyth, C., G. Rampley, T. C. Lemprière, O. Schwab, and W. A. Kurz. 2017. Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. *Glob. Change Biol. Bioenergy* 9(6):1071–1084.
Textile Exchange. 2022. Preferred fiber and materials market report. https://textileexchange.org/wp-content/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf. Accessed March 15, 2023.
Thorbecke, M., A. Pike, and D. Eggers. 2019. Life cycle assessment of corrugated containers and reusable plastic containers for produce transport and display. Quantis International. https://www.corrugated.org/wp-content/uploads/2019/06/CPA_Comparative_LCA_Quantis.pdf. Accessed June 14, 2023.
Tile Council of North America. 2020. Ceramic tile: Industry-wide EPD products manufactured in North America. Tile Council of North America, Anderson, Indiana.
US Energy Information Administration (EIA). 2023. February 2023 Monthly Energy Review OE/EIA-0035(2023/2). www.eia.gov/mer. Accessed March 13, 2023.
US Environmental Protection Agency (EPA). 2022a. Inventory of U.S. greenhouse gas emissions and sinks:1990–2021. EPA 430-R-22-003. US Environmental Protection Agency, Washington, DC. https://www.epa.gov/. Accessed March 2, 2023.
US Environmental Protection Agency (EPA). 2022b. National Overview: Facts and Figures on Materials, Wastes and Recycling. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials#Combustion. Accessed March 2023. Accessed March 2, 2023.
Vlosky, R. 2009. Statistical overview of the U.S. wood preserving industry: 2007. Southern Forest Products Association, Kenner Louisiana. 34 pp.
Zhang, B., K. Lan, T. B. Harris, M. S. Ashton, and Y. Yao. 2023. Climate-smart forestry through innovative wood products and commercial afforestation and reforestation on marginal land. Proc. Natl. Acad. Sci. USA 120(23):e2221840120.
Zhu, K., J. Zhang, S. Niu, C. Chu, and Y. Luo. 2018. Limits to growth of forest biomass carbon sink under climate change. *Nat. Commun*. 9(1):2709.