Forest Carbon Modeling Resource Guide

Topic 4: Forest Products Data and Modeling Considerations

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Introduction

Harvested wood products (HWPs) play an important role in carbon dynamics via carbon storage, emissions, and substitution. This Resource Guide lays out key data resources and tools for HWP carbon modeling as well as a discussion of additional modeling considerations.

Available Databases, Tools, and Resources

Timber Product Output Data

Timber Product Output (TPO) studies are conducted by the USFS Forest Inventory and Analysis Program (FIA) and estimate industrial and non-industrial uses of roundwood across the US and provides mill utilization data, primarily submitted for Resource Planning Act (RPA) assessment. TPO data records contains eleven quantitative and qualitative variables on roundwood, including ownership, species, source, product, and three different types of volume. TPO data generally reports timber harvest, mill residues, and logging residue utilization by primary milling facilities across US counties and states. However, it is important to note that the wood utilization data from TPO is not readily available for all states. See the FIA TPO program website for more details about available data: https://www.fia.fs.usda.gov/program-features/tpo/.

While TPO data are not readily available for all states, periodic state-level RPA assessments on mill activity (produced every five years) provide much of this important mill data. RPA Assessments use the most recent state TPO survey for each reporting year (e.g., the 2012 report will provide state-level data on mill behavior that may have been conducted any year between 2008 and 2012); an appendix table details the year in which each state's data was collected (available here: https://www.fia.fs.usda.gov/program-features/rpa/).

Calculating TPO Data

TPO data collection includes a bi-annual primary forest products manufacturing mills survey as well as some voluntary reporting. The TPO data collection effort is generally supported by a variety of state agencies in collaboration with the USFS FIA program.

Primary wood-using industries included in the analysis include pulp mills, sawmills, veneer mills, composite panel mills (e.g., oriented strand board or OSB), and other industrial products mills. These mills convert roundwood products (e.g., saw logs, veneer logs, pulpwood, etc.) into primary wood products such as lumber, veneer or sheathing, poles and posts, and wood pulp.

Accessing TPO Data

TPO data is available to the public through the USDA Forest Inventory and Analysis National Program (https://www.fia.fs.usda.gov/program-features/tpo/). TPO Studies include the following toolkits and program features:

One-click Factsheets: Users click on the desired state on the map to produce a real-time fact sheet of that state based on current TPO data. Data include state-wide production, products, number of primary mills and types, roundwood exports/imports and retained production.

Interactive Reporting Tool: Users Click on the desired state(s) or counties on the map to produce TPO data based on the geographic area and year of interest. The TPO Interactive Tool includes estimates of timber products, logging residue, mill residue, residential fuelwood, and other removals based on the selected area.

Data Download: Provides TPO data in .xlsx file format. Data included for download are the most granular state and county level data publicly available to users. These files allow visitors to produce estimates of timber products, logging residue, mill residue, residential fuelwood, and other removals at the state and county level.

Legacy Reporting Tool: Allows visitors to produce estimates of timber products, logging residue, mill residue, residential fuelwood, and other removals at the county and state level in table format. This tool includes legacy data, but data will not be updated or added.

TPO Explorer: Allows visitors to investigate the spatial and temporal patterns of round wood production, logging residues, mill residues, residential fuelwood, and other removals. This tool will also visitors to pattern mill locations by type of production and other attributes and map county and state estimates by different categories such as owner, species, source, etc.

Using TPO Data in Carbon Modeling

TPO data are extensively used to estimate the carbon accounts of harvested wood products, including the amount of carbon that is stored in, emitted by, and substituted by HWPs. Such analyses, the components or which are detailed below, depend on an accurate understanding of the current, or baseline, mill activity that TPO data provide.

In general, application of TPO data beyond the toolkits is complex and requires expert knowledge to conduct scenario analysis (i.e., the carbon storage, emissions, and substitution of HWPs across diverse harvest and production regimes) in accordance with study needs.

Additional Applications for TPO data

TPO data and ecological models can tell us on how much wood is *available* from a forest or landscape; however, harvest is dictated not only by what is available, but also by the demand from the mills, which is itself impacted by price and capacity dynamics. TPO data account for the utilization of roundwood and thus provide an estimate of what is currently harvested; they can additionally be used as inputs and to contribute toward assumptions for scenario development and in other types of analyses:

Market Analysis: Most carbon modeling with an associated market analysis use TPO data in conjunction with other data sources. Some of the more popular models include the Land Use and Resource Allocation modeling system (LURA), Forest and Agricultural Sector Optimization Model (FASOM- GHG), or the Sub-Regional Timber Supply Model (SRTS). TPO data are generally used to understand and estimate the demand for roundwood and potential availability of additional wood supply in the state. In these modeling frameworks, these data are also used to evaluate industry and policy response to forest product industry.

Economic tradeoff analyses: assessments of the relative economic benefits and tradeoffs across diverse forest management scenarios (e.g., determining the costs per acre of delayed harvest relative a baseline scenario). Such analysis may motivate or justify political support, e.g., via tax incentives or technical assistance, for certain practices that might otherwise be seen as cost-prohibitive for private landowners. They can additionally help private and public landowners determine the most cost-effective climate-smart interventions for their land.

Demand Analyses: The demand for wood products is increasing. TPO data can help identify trends and prioritize components of the wood supply chain that are in greatest or increasing demand.

Informing mill investment decisions: TPO data can help inform the current demand for HWPs and so the feasibility of establishing new timber processing facilities, among other questions.

Additional Databases, Tools, and Resources on Mill Product Data

Additional databases or providers for mill and product data include:

Fastmarkets RISI: provides global price reporting and market analysis for the forest products sector including pricing for pulp and paper, packaging, lumber, timber, biomass, and tissue.

Forest2Markets: third-party reporting service that provides pricing and cost benchmarks for the wood raw materials supply chain including products such as timber, lumber, and wood fibers as well as forecasting reports for the forest industry. Additionally, US and Brazil data are available for landscape-level estimates of growth, inventory, and harvests.

TimberMart-South: source for current and long-term trend data for stumpage and delivered wood prices for the Southeastern USA. Publishes quarterly and annual reports to assess market pricing in 11 states including: Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas and Virginia

Timber Mart North: Price reports for state-by-state stumpage pricing by species and products for Michigan, Minnesota, and Wisconsin. Provides semi-annual prices based on weighted averages of public agency timber sales in the region.

Corporate Reports: E.g., Western Forest Products Quarterly and Annual reports detailing information on product sales and revenue.

State Agencies: E.g., Michigan, Wisconsin, and Minnesota DNRs conduct periodic surveys to collect mill location and other data, all made available online in diverse formats.

Private or non-profit organizations: E.g., The Nature Conservancy as well as state-level forest product councils or forest product industry associations often collect and report data on mill activity and price dynamics.

Future Directions

The FIA TPO program is uniquely suited to address the demand and supply of forest products and can fulfill future monitoring requirements of forests and greenhouse gas emissions associated with the forest sector. Most of the available data is for southern and pacific northwestern states. Continued development and enhancement of tools is necessary to expand the extent of the FIA TPO database and to get information into the hands of all stakeholders, from smallholder forest owners to state policymakers.

Forest Product Carbon Modeling: Data Needs and Considerations

Modeling the carbon stored in, emitted by, and displaced by HWPs requires data and assumptions about how we use and dispose of our timber. Harvested wood products do not store carbon equally; some products remain in use for longer periods of time (i.e., they have not decomposed or been burned), ultimately storing carbon for longer periods of time. Further, when considering alternative forest product *scenarios* (i.e., divergences from baseline activity), the carbon potential of any HWP will depend not only on its own lifecycle and associated storage and emissions, but also on those products for which it is assumed to have substituted (if any).

Accurate estimates of the role HWPs play in carbon storage and emissions require, first, an ability to track carbon through space and time. Where is it going? How long is it projected to stay there? What are the conditions for its eventual emission into the atmosphere (e.g., via decomposition in a landfill or burning)? To calculate the carbon impact of HWP production *scenarios*, additional considerations must be made to account for product substitution and leakage. Each of these components will be discussed in turn. While default estimates exist for each category, carbon estimates will be more accurate with more precise and regionally- or state-specific data.

Product Proportions

To the first question (i.e., where is it going), one needs estimates for the proportion of different products produced from a timber harvest and its mill residues, both domestically and internationally. Domestically, these product proportions can be calculated from TPO and state mill data. FAOSTAT, a free database for food and agriculture data (including the forest sector) provided by the Food and Agriculture Organization of the United States, provides data on country-level HWP imports, exports, and production, which can be used to make assumptions about the fate of industrial roundwood exports. Note that these data are country-reported; accordingly, accuracy may vary by country.

While TPO data contain estimates of the volume and destination of exported roundwood, they do not account for re-exports (i.e., exported material that did not originate in the state of departure, but which entered the state en route to exportation). Commodity Flow Survey (CFS) data, a joint effort by the Bureau of Transportation Statistics, U.S. Department of Transportation, and the U.S. Census Bureau, provide primary source data of domestic freight shipments; these may help inform interstate trade flows in order to determine a more accurate estimate of exported, state-produced roundwood, though TPO and CFS data are not generally reported in the same years. In states for which TPO data are not available, US International Trade Commission (USITC) data on roundwood exports at the port-level may be useful. Other data on HWP imports and exports may be available via state assessments.

Product Lifecycles

Beyond product proportions, one must consider how long, on average, carbon will remain in use after it has been processed and the conditions under which it will eventually be emitted. Here, we must factor in product **half-lives** (i.e., the average time until half of the material is expected to have decayed), which factors in product **end-uses** (i.e., the proportion of the timber product, such as lumber, going toward single-family homes versus furniture, shipping or other end-uses), as well as product **retirement** (e.g., proportions sent to recycling or landfills, burned, or burned for energy capture).

Product **half-lives** (HL) refer to the average amount of time it takes for half of a product to have decayed and are calculated using the equation:

$$HL = \ln 2/k,$$

where k is a first order decay coefficient (IPCC, 2006). Note that *timber product*-level HLs will vary depending on assumed longevity of the end use products those timber products are assumed to go toward. E.g., the lifespan of lumber will depend on what one assumes a state does with that lumber and at what proportions. Lumber will have a significantly higher HL if a state assumes the majority of its lumber goes toward single-family homes (with a HL of 78-350 years) rather than pallet production (with a HL of 1-2 years). See Dymond (2012) and Skog and Nicholson (1998) for estimated HLs at the product level. Howard, McKeever, and Liang (2017) provide estimates of wood product market share by end use in the US (2012-2017), though these numbers undoubtedly mask variation across US states.

When region specific data is unavailable, default HL information can be substituted. The IPCC (2003) default HLs for wood products are: 2 years for paper products, 35 years for sawnwood, 30 years for veneer, plywood, and structural panels, and 20 years for non-structural panels. State and country-level analysis provide much greater variation depending on the data available. Given softwood and hardwood go proportionally to different end uses in the US (e.g., a significantly higher proportion of soft sawnwood goes toward shipping – see Howard, McKeever, and Liang, 2017). A best practice would be to calculate and assign species-specific HLs accordingly and, if possible, by state/ region.

Retirement

Each commodity has a corresponding half-life that determines the longevity of the carbon in use before being allocated to an end-of-life pathway (i.e., recycled, burned, burned for energy, or sent to the landfill) and, eventually, emitted back to the atmosphere. Retirement considerations are crucial for HWP carbon estimations and scenario-development for a host of reasons, including: 1) shifts in retirement toward more recycling prolong the time until eventual decay and carbon emission (maximizing HWPs' carbon storage potential); 2) shifting retirement proportions toward retirement or burning for energy use will have substation benefit implications; and 3) the proportion of wood products going toward landfills will determine rates of carbon as well as methane emissions from those landfills. Specific consideration should be paid to landfill emissions, in particular acknowledging that diverse wood products decay in landfills at different rates (e.g., while IPCC defaults for landfill emission differ across climate zone, paper waste typically decays twice as quickly as wood waste – see Pipatti et al., 2006) and that landfills themselves differ in their product-level decay rates as well as how they manage GHG emissions. All of these dimensions will impact total HWP carbon storage and GHG emissions, including methane emissions from landfills.

Product Substitution (Displaced Emissions)

Life Cycle Assessments (LCAs), or an assessment of a product's extraction, transportation, and manufacture emissions (scope 3 emissions), consistently reveal that lumber and wood panels used in construction store more carbon, emit fewer GHGs, and use less fossil fuel energy than steel, concrete, brick, or vinyl, whose manufacture is energy-intensive and produces substantial carbon emissions. In cases where HWPs are assumed to substitute for alternative, more emissions-intensive products (e.g., concrete, steel), the change in production of those commodities relative to the baseline is associated with **displaced emissions** (or **substitution benefits**). Likewise, a *decrease* in harvest and commodity production may be associated with *increased*, or positive, emissions in cases when more emissions-intensive products are assumed to substitute for the less emissions-intensive wood products. *Substitution dynamics are important for scenario analysis only and are not included in GHG land sector emissions reporting.*

Substitution Calculations

Substitution, or displaced emissions, can be calculated at the harvest-level or for more nuanced categories, e.g., by softwood or hardwood harvest or at the timber product or end-use level. All such calculations represent the *change* in emissions associated with shifts in production (either due to shifts in overall production or shifts in product proportions holding total harvest constant). Substitution benefits are assessed relative to a baseline or BAU scenario to account for shifts in product use.

See Smyth et al (2017) for a detailed look at how the Canadian Forest Service estimates economy-wide wood product and bioenergy substitution benefits at the national level. Employing Smyth et al (2017)'s methods, but parameterizing with California data, Cabiyo et al (2021) estimate substitution benefits at the state as well as product level, looking at the potential substitution benefits due to shifts in forest residue use in particular. Bergman et al (2014) compile important wood and substitution product LCA data that can be used or reference in substitution calculations, including average product mass, weight, biogenic carbon content, and extraction, transportation, and manufacture emissions across different US regions. Additional or alternative data and methodological needs will depend on the region and product scenario specifics.

Substitution Benefit Calculations from the Literature

Degree of carbon benefit (a way to compare across production scenarios) is captured by a calculated **displacement factor (DF)**, or the change in emissions achieved per each additional unit of wood used. It applies only to *changes* in wood use relative a baseline scenario and not all harvested wood. In a meta-analysis of 21 studies, Sathre and O'Connor (2010) find a that DFs (across a series of wood products in different locations) range from -2.3 to 15, with an average DF of 2.1 tC (i.e., an average of 2.1 tC emissions avoided per each additional tC of wood product produced). Smyth et al (2017) assess sawnwood and panels separately to estimate DFs of 0.54 tC and 0.45 tC, respectively. They calculate bioenergy DFs of .47 tC and 0.89 tC, the variation resulting from of differing underlying assumptions (more specifically, the latter number constrains energy substitution to target fossil fuel heat demand).

Cabiyo et al (2021) calculate higher DFs in California relative Canada following the same methodology parameterized for California. They estimate low and high sawtimber DFs to be 0.75 and 1.75, respectively. Their bioenergy DF assessments more closely link with those of Smyth et al (2017), with a low estimate of 0.11 and a high estimate of 0.81. They additionally assess the substitution benefits associated with diverse residue pathways; calculated DFs for residue products range from 0.1 for biopower all the way to 0.94 for GluLam (Glue laminated timber) and OSB (Oriented Strand Board) production.

While these numbers may provide useful benchmarks or defaults, accurate carbon benefits necessitate regular assessment and, where possible, the use of updated and regionally-appropriate data and assumptions. DF calculations depend directly on the emissions associated with wood product emissions *as well as the emissions stemming from those products they are assumed to substitute for*. As such, calculated DFs will vary dramatically where 1) product and end-use proportions differ (e.g., Cabiyo et al (2020) calculate a net substitution value in California higher than that which Smyth et al (2017) calculate for Canada due to a larger fraction of baseline timber products in California going toward building construction); and 2) counterfactual emissions vary (i.e., the emissions associated with alternative products differ across states and regions). As an increasingly important example of the latter, many states are enacting clean energy programs; where they are successful at achieving their renewable energy goals, bioenergy can no longer be credited with displacing those energy emissions in scenario analyses.

Key Consideration for Substitution Calculations

Substitution benefits are often reported as a key benefit of HWP production, but accurate assessments must entail, where possible, region-specific estimates of product suitability, demand, and leakage. Howard et al (2021) provide a critical review of existing substitution assumptions in HWP carbon analyses, attention to which will make for more accurate substitution analyses.

Product Feasibility and Demand

Realistic substitution scenarios need to take into consideration limitations to both production and demand. For instance, it may be unrealistic to assume that all additional harvest relative the baseline might go toward particular products or even toward baseline product proportions. Similarly, holding baseline harvest amounts constant, it may be unrealistic to assume that timber production proportions can be easily shifted. First, not all timber is suitable for all products; second, such assumptions do not consider price and demand dynamics. Products cannot be indefinitely substituted due to physical, price, and other constraints; determining the limits of realistic production shifts and product demand are necessary components of substitution analysis.

Recent research explores product scenario feasibly from a host of dimensions (including realistic product suitability, availability, and demand). As some examples, see Swinton et al (2020) on limits to using logging residues for biomass, Nepal et al (2021) on global demand for mass timber, Zhen & Aguilar (2013) on consumers' willingness to pay for certified wood products, Aguilar et al (2014) for a related look at the impact of price on willingness to harvest, and Shahi et al (2021) for a look at the impact of prices on construction material choices.

Leakage

A related consideration to product price and demand analysis is that of production **leakage.** Leakage typically refers to displaced activities that occur *outside* of the intervention area (or the hypothetical intervention area in the case of HWP carbon modeling – e.g., a state) that are a direct result of intervention activities. Intervention, here, might refer to a shift in forest management or timber production activities leading to a shift in available HWPs. As an example, assuming constant demand, harvest *reduction* in one state or jurisdiction may lead to *increased* harvest in a neighboring state. The same logic applies at the product level, e.g., a reduction in pulp production in one state may lead to an increase in pulp production in a neighboring state, again, assuming constant demand.

Leakage dynamics impact HWP production dynamics as well as those of any HWP substitutes; accordingly, they directly impact product substitution assessments. As an example, under a scenario in which overall harvest increases in a specific state, what percent of that additional harvest is assumed to *substitute* for more emissions-intensive product demand (leading to negative, or displaced, carbon emissions) and what percent will instead flow to neighboring states, who will have reduced harvests accordingly (leading to no product substitution)? On the other side of the spectrum, in the case of a state-level reduction in harvest, what percent of that missing timber, assuming constant demand, will be substituted with *more* emissions-intensive products (e.g., increasing the steel/ concrete proportions of material use in construction, increasing the scenario's positive carbon emissions) and what percent will instead be met with increased imports from (and harvest in) neighboring states?

Accurate state-level leakage rates will depend on the nature of the products and markets in question (e.g., including product elasticity) as well as on the degree of assumed regional collaboration (for instance, one can assume less leakage when neighboring jurisdictions engage in similar shifts in harvest and production). US leakage estimates in the literature range from 63.9% with regional collaboration (Gan and McCarl 2007) to 84.4% without (Wear and Murray 2004); leakage at the state or subnational level may reasonably be even higher given the reduced constraints for interstate (relative international) trade.

Substitution and GHG Reporting

Importantly, while substitution benefits associated with HWPs are important for the assessment of forest management and policy alternatives, to avoid double-counting, they are not included in official reporting of GHG emissions and removals in the land sector; rather, they will be evident (should they exist) in emissions reductions in other sectors. Those reported emissions reductions will thus be based not on *assumptions* about product suitability, demand, and leakage, but on any actual substitution and leakage that may have occurred.

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Zhen Cai and Francisco X. Aguilar (2013), "Meta-analysis of consumer's willingness-to-pay premiums for certified wood products", Journal of Forest Economics: Vol. 19: No. 1, pp 15-31. http://dx.doi.org/10.1016/j.jfe.2012.06.007

Additional Resources

Webinars/Videos

DeLyser, K. and Papa, C. (May 2022). Modeling Forest Management and Carbon: A Tool for State-Wide Planning and Action. [Webinar presentation]. Forest-Climate Working Group Learning Exchange Series, MSU Forest Carbon and Climate Program

Kurz, W. (June 2017). The Role of Forests and Forest Products in Decarbonization. Pacific Institute for Climate Solutions' Forest Carbon Management Project.

Pasternack, R., Belair, E., and Wang, Y. (March 2022). Emerging Climate-Oriented Bioeconomy Frameworks: A Central Role for Forests. [Webinar presentation]. Forest-Climate Working Group Learning Exchange Series, MSU Forest Carbon and Climate Program

Ganguly, I. and Puettmann, M. (April 2022). Recent Findings on Building-Scale Carbon LCAs and Demand-Driven Landscape Impacts. [Webinar presentation]. Forest-Climate Working Group Learning Exchange Series, MSU Forest Carbon and Climate Program

Peer reviewed resources

Arehart, J.H., Hart, J., Pomponi, F. and D'Amico, B. (2021). Carbon sequestration and storage in the built environment. Sustainable Production and Consumption, 27, pp.1047-1063.

- *This document quantifies and compares the effects of carbon sequestration and storage in buildings from a life cycle perspective.*

Breton, C., Blanchet, P., Amor, B., Beauregard, R. and Chang, W.S. (2018). Assessing the climate change impacts of biogenic carbon in buildings: A critical review of two main dynamic approaches. Sustainability, 10(6), p.2020.

- *This article discusses increasing the use of harvest wood products from sustainably managed forests to provide climate mitigation benefits and carbon storage. It critically reviewed life cycle assessment methodologies and measurements and compares two main LCA approaches.*

Chen, J., Ter-Mikaelian, M.T., Yang, H., Colombo, S.J. (2018). Assessing the greenhouse gas effects of harvested wood products manufactured from managed forests in Canada, Forestry: An International Journal of Forest Research, Volume 91, Issue 2, Pages 193–205

- *This article presents a new life-cycle analysis system developed by the authors to quantify carbon dynamics for Canadian-made harvested wood products.*

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. Nature Sustainability, 3(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

- Assessment of engineered timber's potential to substitute for traditional construction.

Clay, K., & Cooper, L. (2022). Safeguarding against Harm in a Climate-Smart Forest Economy: Definitions, Challenges, and Solutions. Sustainability, 14(7), 4209. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su14074209

- While HWPs have the potential to provide net carbon benefits through carbon storage and product substitution, it cannot be assumed that they will do so. This report details the importance of (and challenges for implementing) social and environmental safeguards for a climate-smart forest economy.

Favero, A., Daigneault, A. and Sohngen, B. (2020). Forests: Carbon sequestration, biomass energy, or both?. Science Advances, 6(13), p.eaay6792.

- *This article aims to clarify the controversy and debate surrounding the role that wood bioenergy pays in climate mitigation. It discusses topics relative to woody biomass demand, such as demand on forest harvests, prices, timber management investments and intensity, forest area, and carbon balances under different climate mitigation policies.*

Geng, A., Yang, H., Chen, J. and Hong, Y. (2017). Review of carbon storage function of harvested wood products and the potential of wood substitution in greenhouse gas mitigation. Forest Policy and Economics, 85, pp.192-200.

- *Literature review aims to (a) clarify the methodological issues in greenhouse gas effects assessments of harvested wood products and wood bioenergy substitution, (b) summarize and compare the reported GHG effects, and (c) identify knowledge gaps to inform future research.*

Jasinevičius, G., Lindner, M., Pingoud, K. and Tykkylainen, M. (2015). Review of models for carbon accounting in harvested wood products. International Wood Products Journal, 6(4), pp.198-212.

- *This study analyzes and finds relevant features of existing carbon accounting models for harvested wood products. It describes shortcomings of models, such as a lack of climate change mitigation potential, as well as propositions to increase the effectiveness of models.*

Johnston, C.M. and Radeloff, V.C., (2019). Global mitigation potential of carbon stored in harvested wood products. Proceedings of the National Academy of Sciences, 116(29), pp.14526-14531.

- *Paper estimates the carbon stored in harvested wood products from 1961 to 2065 for 180 countries. It uses IPCC carbon-accounting guidelines, historical data, and plausible features to create projections.*

Korhonen, J., Nepal, P., Prestemon, J.P. *et al.* (2021). Projecting global and regional outlooks for planted forests under the shared socio-economic pathways. *New Forests* 52, 197–216.

- *Uses recently published data on planted forests by country to estimate relationships between per capita income and planted forest area.*

Leskinen, P., Cardellini, G., González-garcía, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C., Stern, T., & Verkerk, P. J. (2018). Substitution effects of wood-based products in climate change mitigation. From Science to Policy, 7(European Forest Institute).

- An exploration into the mitigation and substitution potential of wood products, including links to policymaking.

Pasternack, R., Wishnie, M., Clarke, C., Wang, Y., Belair, E., Marshall, S., Gu, H., Nepal, P., Dolezal, F., Lomax, G. and Johnston, C., (2022). What Is the Impact of Mass Timber Utilization on Climate and Forests?. Sustainability, 14(2), p.758.

- *Literature review to assess the total climate impact of forest product demand across product substitution, carbon storage in materials, current and future forest carbon stock, and forest area and condition to understand the impact of increased mass timber utilization on forests and climate.*

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