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ORIGINAL ARTICLE

Carbon storage potential of harvested wood: summary and policy implications

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Abstract Within national greenhouse gas inventories, many countries now use widely-accepted methodologies to track carbon that continues to be stored in wood products and landfills after its removal from the forest. Beyond simply tracking post-harvest wood carbon, expansion of this pool has further been suggested as a potential climate change mitigation strategy. This paper summarizes data on the fate of carbon through the wood processing chain and on greenhouse gas emissions generated by processing, transport, use and disposal of wood. As a result of wood waste and decomposition, the carbon stored long-term in harvested wood products may be a small proportion of that originally stored in the standing trees—across the United States approximately 1% may remain in products in-use and 13% in landfills at 100 years post-harvest. Related processing and transport emissions may in some cases approach the amount of CO_2e stored in long-lived solid wood products. Policies that promote wood product carbon storage as a climate mitigation strategy must assess full life-cycle impacts, address accounting uncertainties, and balance multiple public values derived from forests.

Keywords Carbon sequestration · Greenhouse gas emissions · Harvested wood products · Offsets · Life-cycle assessment

1 Introduction

Increasing consensus around the need to address human-induced climate change has inspired a variety of proposals to control emissions and enhance sequestration by changing forest management. The conversion of forests to other land uses accounts for a significant portion of cumulative global anthropogenic greenhouse gas emissions, so climate policies

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that prevent deforestation or reforest cleared lands enjoy widespread support. There is less unanimity regarding the potential to increase carbon sequestration by changing management of existing forests or by increasing the storage of carbon off-site in wood products or landfills.

National greenhouse gas inventories that comply with the United Nations Framework Convention on Climate Change (UNFCCC) may report carbon stored in harvested wood products following guidelines developed by the International Panel on Climate Change (IPCC 2003; IPCC 2006). The United States Environmental Protection Agency Inventory of Greenhouse Gas Emissions and Sinks (US EPA 2010b), for instance, indicates that the pool of carbon stored in wood products and landfills from timber harvested in the United States increased by approximately 88×10^6 t of carbon-dioxide equivalent (CO_2e[1]) in 2008.

Beyond simply tracking harvested wood carbon pools in national-level greenhouse gas inventories, expanded use of wood products has also been suggested as a climate change mitigation strategy (Malmsheimer et al. 2008; Perez-Garcia et al. 2005; Skog 2008; Tonosaki 2009). However, inventories are insufficient to identify policy actions that can lower total GHG emissions, because they do not indicate how changes in one element (like harvested wood carbon) will change other elements (like forest carbon stocks or emissions from energy and waste sectors). Only more detailed life-cycle assessments (LCAs) can provide information about the net impact on atmospheric greenhouse gas (GHG) concentrations.

Section 2 of this paper summarizes data from GHG life-cycle assessments for wood products, drawing upon general indicators of carbon transfers where LCAs are not available. Section 3 considers how life-cycle data can inform decisions about the treatment of wood products in project-based climate mitigation efforts, followed by discussion and conclusions in Section 4.

2 Greenhouse gas impacts of wood products

A comprehensive LCA for a solid wood product might begin with the harvesting of trees and end with the disposal and decomposition of wood products made from those trees. At each link in the processing chain, a portion of the wood is transformed into waste. Waste wood may be incorporated into other products, burned, or transferred to landfills or other waste sites where much of the wood will decompose. Smith et al. (2006) provide estimates of the fate of harvested wood carbon by broad product categories and United States regions. In this paper, we present additional details on wood waste at the harvest site, secondary manufacturing waste and methane emissions from landfills. We also summarize a selection of individual product LCAs to illustrate the range of variation in the percentage of carbon retained in long-term storage. This variation highlights the importance of collecting data relevant to each mitigation project.

Transportation of wood to mills, industrial processes that transform wood into a variety of products, and delivery to customers and eventually to landfills also release greenhouse

[1] Carbon-dioxide equivalent (CO_2e) permits aggregation of all greenhouse gases into a single metric based on global warming potentials over 100 years. Wood carbon is converted to CO_2e by multiplying by 3.667 to account for the oxygen combined with carbon as it burns or decomposes. This is a simplification that may underestimate the global warming potential represented by intact wood stocks, as some decomposing wood may be released in other forms.

gases. Several life-cycle assessments report GHG emissions for primary products, while fewer assess secondary manufacturing and later product life stages. Measurement methods and units vary, so we convert to metric tons of emissions as CO_2e per ton CO_2e in the final product.[2] As for losses due to processing waste, the variation in emissions among different products and distribution chains[3] indicates the importance of developing project-specific data using methods illustrated by the studies cited here.

Since paper is generally acknowledged to be a net emitter of greenhouse gases (Skog et al. 2008 pp. 6 and 9),[4] this summary focuses on longer-lived solid wood products alone. We also address only direct impacts given current technologies.[5] See Section 2.3 of this paper for a general discussion of substitution and other indirect effects, including biomass energy substitution for fossil fuels.

2.1 Carbon lost from harvest, processing, use and disposal of wood

Carbon is released through decomposition or combustion of waste material during successive steps in the wood products chain: (1) harvest, (2) primary processing, (3) secondary processing and construction, (4) product use and maintenance, and (5) ultimate disposal. Figure 1 illustrates mid-range estimates of the percent of CO_2e originally stored in a standing tree that remains at each stage of processing and use. We use carbon remaining 100 years after harvest as an indicator of climate benefits.[6]

2.1.1 Harvest

Significant amounts of carbon are released during and after timber harvest when logging wastes are piled and burned, are left at the harvest site or at a landing to decompose, or are collected and burned as biomass energy. The USDA Forest Service (2008, Table 40) estimates logging wastes at 30% of roundwood volume for the United States as a whole, with state-level percentages ranging from 3% to 84% (USDA Forest Service 2007).[7] The wide range of estimates reflects differences in size and quality of trees harvested, prevailing harvest technology, and commercial utilization in each region. When roots, stumps, and small limbs left on-site (about 19% of total tree volume (Li et al. 2003) and not normally

[2] See Supplementary materials for computation details.

[3] Emissions reported in a solid wood products survey by Skog et al. 2008 varied as much as five orders of magnitude for facilities producing similar products.

[4] High-lignin papers may remain in landfills for a considerable time, but the methane released from the breakdown of land-filled paper and the energy required for paper production outweigh any carbon storage benefit. The assumption that paper production contributes little on balance to mitigating GHG emissions could change if a greater percentage of paper were recycled or if more of the methane generated by land-filled paper were captured for energy generation.

[5] Thomassen et al. (2008) compare 'attributional' and 'consequential' LCA approaches. We follow the attributional approach here, which measures impacts given current technologies and consumption patterns. Consequential LCA would predict effects after markets respond fully to a change in use of the LCA product. Though it may better reflect the ultimate impacts of policies that change production patterns, consequential LCA estimates are less certain than those for an attributional LCA.

[6] UNFCCC used 100 years for global warming potential calculations (Forster et al. 2007) and the United States Department of Energy in its voluntary greenhouse gas registry (often called 1605(b)) also uses 100 years to assess long-term carbon storage.

[7] Specific gravity of branches and stemwood are highly correlated (Swenson and Enquist 2008), so percentages by volume can be used to approximate percentages by mass. Lowest state values are for states with very low harvest volumes, including Nevada, New Jersey and Rhode Island. Given reliance on surveys for Timber Product Output data, small sample size may affect these estimates.

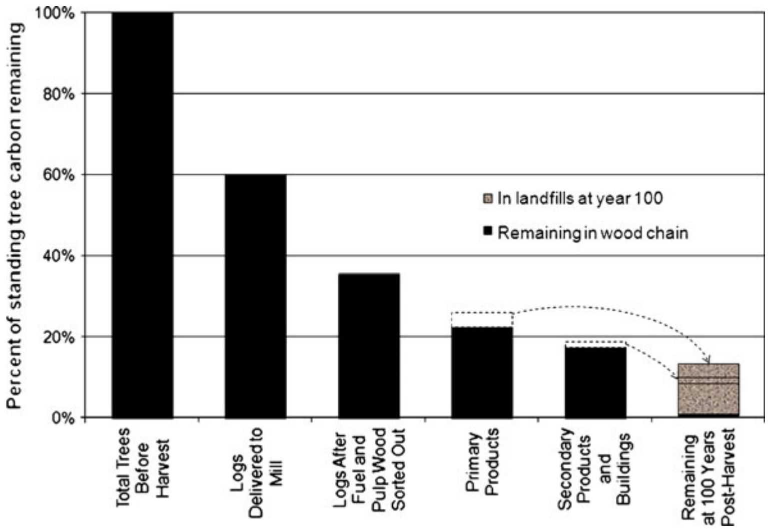

Fig. 1 The quantity of carbon remaining in products made from harvested wood (*black bars*) decreases as it passes through distinct steps in the processing chain. A portion of the loss from some stages is transferred to landfills for further storage (*dotted outlines* and *speckled grey bar*)

measured as part of logging residues) are added to the total, the quantity of logging wastes increases to about 40% of standing tree volume (the difference between the 1st and 2nd bars in Fig. 1).[8]

Zang et al. (2008) estimate that most logging wastes release their carbon over a period of a few years.[9] Since we consider significant carbon benefits to require storage for 100 years, we have simplified accounting by combining all carbon released as a result of logging activity, without regard to exact timing. More detailed investigation would be helpful to clarify the fate of logging residue over time by size of material, species, and local conditions.

2.1.2 Primary processing

Long-term carbon storage benefits derive mainly from the sawlog portion of harvested volume; wood used for fuel or pulp and bark removed at the mill can be considered sources of relatively rapid carbon losses.[10] The diversion of material into fuel and pulp accounts for about 24% of original tree volume for the United States as a whole (difference between 2nd and 3rd bars in Fig. 1).

[8] Carbon released consequent to logging would eventually occur through natural tree mortality; but logging will release carbon over a few years that would have remained intact in living trees for several decades or even centuries in the absence of harvest activity.

[9] See Supplemental materials for conversion of first-order decay k value from Zhang et al. (2008) to half-life for logging residue.

[10] Wood processing byproducts used for fuel are not included in fuelwood percentages, since carbon losses from this source would already be included as part of processing waste. Since bark may already be included in primary mill waste as well as in fuel and pulpwood volumes, we also assume conservatively that this loss is already accounted for under other categories.

Remaining material available for conversion into long-lived products undergoes milling at a sawmill or other primary processing facility. Primary mill waste varies considerably depending on product and equipment used. A variety of LCAs for lumber and panels (Bergman and Bowe 2008; Kline 2005; Liski et al. 2001; Milota et al. 2005; Rivela et al. 2006; Rivela et al. 2007; Wilson and Sakimoto 2005)[11] report primary mill wastes range from about 5% to 22% of the original standing tree volume (mid-range of 13% is the difference between 3rd and 4th black bars in Fig. 1). Wastes are generally lowest for panels that use low-grade wood fibers and highest for finished planed lumber or high-quality plywood.

Processing residues from primary mills may be burned on-site for energy, used to make pelleted wood fuel, converted to structural panels or paper, or dumped or landfilled. For purposes of this summary, we treat the burned portion as an immediate release, and the remainder is assumed to be land-filled at the typical United States rate[12] (dotted outline atop 4th black bar in Fig. 1 represents CO_2e remaining 100 years post-harvest). If wood in landfills lasts longer than paper and panels in use (see Section 2.1.5), our simplifying assumption will increase estimated long-term wood carbon storage, though it may report an excess in landfills rather than in-use at year 100 (last bar of Fig. 1). Detailed information about the proportion of mill wastes used to manufacture long-lived products would be important to assessing the GHG effects of a particular product.

2.1.3 Secondary processing and construction

Once wood leaves the primary mill, further processing may occur to transform the lumber or panels into secondary products. LCA examples for furniture, flooring, and windows yield secondary processing waste estimates from 2% to 18% of original tree volume (BFM, Ltd. 2003; Crumpler 1996; Nebel et al. 2006; Sharai-Rad and Welling 2002; Wood Waste and Furniture Emissions Task Force 1998).[13] Raw lumber that goes directly to the construction site will generate smaller amounts of scrap, ranging from about 1% to 5% of original standing tree volume (National Association of Home Builders Research Center 1995; Wilson and Boehland 2005; Houston Advanced Research Center 2005).

Generally the same wood material will not generate both secondary processing and construction site waste. Most structural materials undergo primary processing only, while secondary products like windows, doors, cabinets and furniture are usually installed without further losses at the construction site. Based on proportion of wood in construction versus other uses in the United States (McKeever 2002, Tables 18, 20, 22), losses from secondary processing and construction combined may amount to about 5% of original standing tree volume[14] (difference between 4th and 5th black bars of Fig. 1). Further research would be helpful to assess the significance and fate of processing wastes for the full range of products at both the secondary mill and construction site.

Combining wastes from logging residues, diversion for fuel and pulp, and primary and secondary mill and construction wastes, typically about 18% of the original live tree volume may be incorporated into finished solid wood products (5th black bar in Fig. 1).

[11] See Supplementary materials for detailed explanations of data extracted from product LCAs and unit conversions.

[12] Portion of primary mill waste that is burned or land-filled is United States average from Smith et al. (2006).

[13] See Supplementary materials.

[14] See Supplementary materials.

2.1.4 Use

Once processing is completed, carbon losses begin to occur as finished products, or portions of products, are disposed of over time. In order to contribute to climate change mitigation, the pool of wood products must increase over time, which is best achieved by keeping products in use for extended periods. About 60% of all primary solid wood materials in the United States find their way into long-lived products such as buildings or furniture (Smith et al. 2006 p. 206). Shorter-lived solid wood products include pallets and other shipping containers and miscellaneous manufacturing (e.g., matches, popsicle sticks, toothpicks).

There is considerable uncertainty about the length of time that wood products remain in use, and assumptions significantly affect estimates of carbon remaining in year 100. Figure 2 compares several alternative assumptions about the longevity of wood products, as presented by Miner (2006).[15]

Before long-lived products reach the end of life, users will discard portions as they make modifications and replacements. Waste from this source makes up about 20% of all wood waste in the United States, more than the waste from new construction (McKeever 2002 Tables 1 and 2).[16] In some cases, half-lives used in wood products accounting apply to the expected life of the wood used in each final product application (which would incorporate effects of discards due to renovation, see Skog 2008). In other cases half-lives appear to be based on the expected life of the final product itself (which would neglect the renovation factor). Additional research would be helpful to quantify carbon losses from this source and to ensure that assumed half-lives for wood products in use reflect this factor.

2.1.5 Disposal

Once discarded, wood products plus a portion of the wood waste from mills and construction sites can continue to store carbon for some time in landfills. Field tests near Sydney, Australia, found that 17–18% of wood carbon had been released by 46 years after disposal (Ximenes et al. 2008). Other studies have assumed that 20% to 80% of land-filled wood is subject to decay, while the remainder is 'pickled' indefinitely (Borjesson and Gustavson 2000). This wide range in estimates reflects limited knowledge about the fate of land-filled wood over multiple decades. Given the relatively short experience with lined and capped landfills and lack of data about how climate, soil, and management influence decomposition, the path of long-term carbon releases from this source (grey portion of the last bar in Fig. 1) remains uncertain; further research could change the assumptions illustrated by this Figure.

Due to anaerobic conditions, over half the carbon released from wood decomposing in landfills will be in the form of methane. After accounting for flaring or burning for energy use the average methane portion for the United States drops to about 20% (US EPA 2006).

[15] The curve labeled 1st order (Smith et al. (2006) revised) uses the following formula: FR=(1/(1+(LN(2)/HL))^Y, where FR is the fraction remaining in use, HL is half-life in years, and Y is years elapsed. Curve is weighted average of solid wood products for the Unites States, with half-lives and product mix from Skog (2008). This curve is used by the United States Department of Energy voluntary greenhouse gas registry (1605(b)) and was used in this paper to estimate carbon remaining in products 100 years after harvest (last black bar in Fig. 1). EFI is European Forest Institute, NIES is the Japan National Institute for Environmental Studies. All formulas are obtained from Miner (2006). Initial stores begin at 18% since that is the approximate portion of standing tree carbon that would initially be incorporated in solid wood products.

[16] See Supplementary materials.

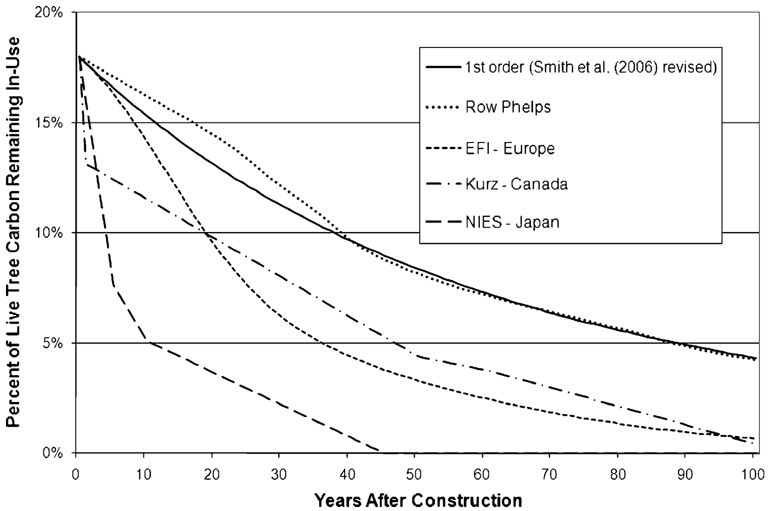

Fig. 2 The longevity of carbon stored in products is determined by how quickly those products are discarded. Alternative models and assumptions yield very different conclusions about long-term storage

Because of methane's greater global warming potential the net GHG benefits at 100 years post-harvest from land-filled wood waste from mills, construction sites, and wood product disposal may be as little as 13% of the CO_2e present in the standing tree (grey portion of last bar in Fig. 1).[17] Open-air waste disposal, more common in some countries, would produce less methane, but would release carbon relatively quickly. Wood waste that is burned for energy rather than being discarded will release its CO_2 immediately and hence will not contribute to long-term carbon storage (however, see 2.3 for a discussion of possible substitution effects).

2.2 Fossil fuel and other greenhouse gas emissions associated with wood products

In addition to the carbon lost through decomposition or combustion of wood waste, the processing and transport of wood products also requires energy, much of it provided by fossil fuels that emit greenhouse gases. Data from a selection of LCA studies which report GHG emissions by stage of life-cycle are summarized below, converted to metric tons CO_2e emitted per metric ton CO_2e stored in finished wood products.[18] The purpose of this summary is to indicate the general magnitude and variability of emissions associated with the conversion of standing trees into products that continue to store a portion of the carbon.

Though many 'gate-to-gate' LCAs exist for specific wood product manufacturing processes, 'cradle-to-grave' LCAs that track emissions from harvest, manufacturing, transport, construction, product use and disposal, and that report GHG emissions for wood

[17] Percent of wastes land-filled and percent subject to decomposition over 100 years is from Skog (2008). See Supplementary materials for calculations of the global warming effects of methane.

[18] Since few timber management operations harvest for long-lived solid wood products alone, expanded use of wood products would increase production of a range of products, including many that do not contribute significantly to long-term carbon retention. Hence the emissions illustrated here, expressed relative to the carbon present in the finished product, would underestimate total emissions impacts of expanded wood products output, which would include emissions from co-products.

components separately, are rare. Figure 3 compares cradle-to-grave LCAs for lumber in three applications: single-family house frames (Consortium for Research on Renewable Industrial Materials (CORRIM)—data from Johnson et al. 2005; Meil et al. 2004; Perez-Garcia et al. 2005; Winistorfer et al. 2005); large multi-story buildings (Sharai-Rad and Welling 2002); and mixed construction and miscellaneous uses (Gower et al. 2006). (See following sections for discussion of emissions from more highly-processed components). As Fig. 3 indicates, emissions may vary considerably from one processing chain to another, and may approach the total CO_2e stored in the final product.[19]

2.2.1 Harvest

Harvest-related activities in the forest emit a relatively small quantity of greenhouse gases, even when transport to the mill, methane from combustion, and nitrous oxide from fertilization are included. These emissions might range from 0.03 to 0.05 t CO_2e per metric ton CO_2e stored in the finished products derived from the log (Johnson et al. 2005; Gower et al. 2006).[20]

2.2.2 Primary processing

Fossil fuel emissions from processing of primary wood products (including rough and planed dry lumber, plywood, oriented strandboard and medium density fiberboard) range from about 0.01 to 0.26 t CO_2e per metric ton CO_2e in finished wood products made from those materials, with the higher emissions from panels (Bergman and Bowe 2008; Gower et al. 2006; Kline 2005; Liski et al. 2001; Milota et al. 2005; Rivela et al. 2007; Wilson and Sakimoto 2005).[21]

[19] Units are metric tons of emissions as CO_2e per ton CO_2e embedded in wood in finished building or other product. The CORRIM analysis applies to shells of two single-family wood-framed homes suitable for southeastern (200 m^2) and northern (192 m^2) climates in the United States; includes roof, siding, and internal walls, but excludes finished floors, trim, doors, cabinets, furniture. Sharai-Rad and Welling (2002) reported emissions for a multi-story simple wood-frame structure, did not report harvest emissions or transport separately, and did not include use/maintenance/demolition, so emissions are shown as a single bar. Gower et al. 2006 assumed lumber was used for new homes 45%, renovations 20%, short-lived projects 20%, and very short-lived projects 15%. Transport from mill to construction site is shown separately to illustrate its potential to influence the total. This assessment omitted emissions from construction and use/maintenance/demolition.

[20] See Supplementary materials for computation details. Data from Gower et al. (2006) includes the GHG emissions from fossil fuel combusted for harvest, skidding and road-building, part of a larger cradle-to-grave LCA for all wood harvested from a western Canadian forest operation in one year. Johnson et al. (2005) calculated emissions from representative operations under low and high intensity management in the northwestern and southeastern U.S. Reported emissions include CO_2, CH_4, and N_2O from harvesting, including loading of trucks, and site preparation, including use of fertilizers. See Supplemental materials for computation details.

[21] Bergman and Bowe (2008) reported gate-to-gate emissions per cubic meter of dry planed hardwood lumber in the northeastern United States. Gower et al. (2006) include the GHG emissions that occur at the sawmill (no transport) from an LCA for all wood harvested from a western Canadian forest operation in one year. Kline (2005) tracked gate-to-gate emissions per cubic meter of oriented strandboard in the southeastern United States. Liski et al. (2001) assessed emissions associated with gate-to-gate lumber and plywood production in Finland. Milota et al. (2005) documented gate-to-gate emissions per cubic meter of planed dried pine lumber in the southeastern United States. Rivela et al. (2007) estimated gate-to-gate emissions per cubic meter of medium density fiberboard. Wilson and Sakimoto (2005) reported gate-to-gate emissions per cubic meter of softwood plywood in the southeastern United States. See Supplemental materials for computation details. Kline (2005), Milota et al. (2005), and Wilson and Sakimoto (2005) provided input to the CORRIM house frame LCA illustrated in Fig. 3, which combines manufacturing with construction emissions.

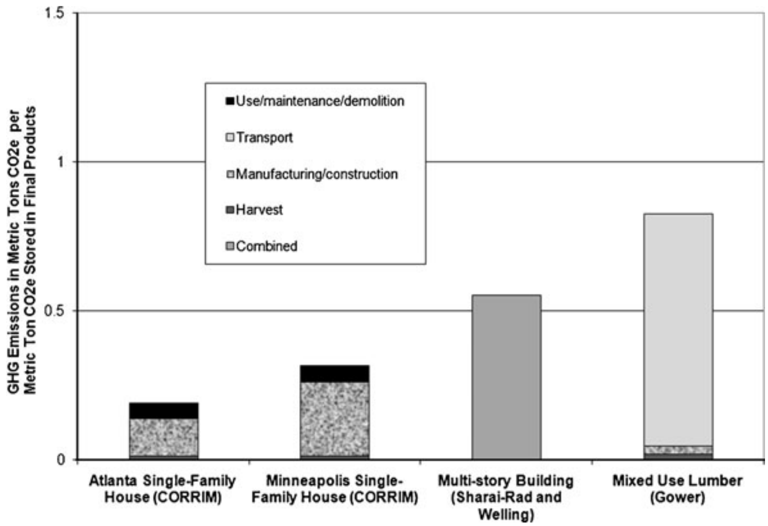

Fig. 3 Greenhouse gas emissions along the processing chain vary widely by manufacturing process and distribution system. The cradle-to-grave LCAs for construction and mixed manufacturing illustrated here estimate emissions at 19, 32, 56, and 83 t CO2e per t CO2e in wood stored in the finished wood products

Transport from mill to construction site or retail outlet may also contribute significant emissions, and this factor varies tremendously depending on the distribution system (Meil et al. 2004; US EPA 2006; Gower et al. 2006; Rivela et al. 2007).[22] The Gower et al. (2006) study included some lumber with a continent-wide distribution system; its value of 0.78 t CO_2e per metric ton CO_2e stored in finished wood products far exceeds emissions from the rest of the wood product chain (see fourth bar of Fig. 3).

2.2.3 Secondary processing and construction

Manufacturing of lumber or panels into secondary products and/or incorporation into buildings emits additional GHGs, but data to assess this component are scarce. A gate-to-gate LCA for wood flooring in Germany (Nebel et al. 2006) starting with lumber as raw material reports fossil energy emissions at 0.33 t CO_2e per metric ton of CO_2e stored in board flooring, and 0.52 t CO_2e for wood block. Four types of parquet flooring (which store less carbon and require more GHG-emitting glues) averaged 1.73 t CO_2e per metric ton of CO_2e stored in the flooring, indicating that highly-processed wood components may have more emissions per ton of wood carbon stored, compared to the building frames illustrated in Fig. 3.

Studies by CORRIM (Meil et al. 2004) calculated total construction emissions for two model houses.[23] If total construction emissions are allocated based on material weights, the

[22] Meil et al. (2004) assessed GHG impacts for construction of the CORRIM model houses described above, including transport from manufacturer to construction site. US EPA (2006) estimated emissions per wet ton of material delivered to a landfill, including those associated with manufacturing of lumber and medium density fiberboard plus transport of raw materials and of finished products to retail. As part of a larger LCA, Gower et al. 2006 reported transport emissions for wholesale distribution of softwood lumber produced in one year from a property in Canada.

[23] Emissions are from construction-site activities required to produce a basic structure (slab or foundation, exterior walls with windows but not doors, interior walls, subfloors, and roof) for wood-based model homes in Atlanta and Minneapolis. (Transportation was reported separately). Emissions were not reported by material component, so the wood portion is estimated based on proportional material weights.

emissions associated with wood components amount to only 0.009 and 0.006 t CO_2e per metric ton of CO_2e stored in the homes' wood materials. Using similar assumptions, an LCA for Central European homes using three different construction methods[24] estimated 0.01 t CO_2e construction-related emissions per metric ton of CO_2e stored in wood (Sharai-Rad and Welling 2002).

Analysis of a wider array of construction types, disaggregation by material, and information from other regions would improve understanding of the magnitude and range of construction-related emissions.

2.2.4 Use/maintenance/demolition

The final rather minor emissions associated with long-lived wood products are those required to maintain products during their period of use and to dispose of them. Maintenance and repairs to the wooden portions of CORRIM's model houses over a 75-year lifespan were estimated at 0.05 t CO_2e and demolition at 0.003 t CO_2e per metric ton per metric ton of CO_2e embodied in the wood portion of the houses (Winistorfer et al. 2005).

2.3 Broader system effects

Beyond the wood losses and associated emissions noted above, timber harvest for wood products manufacturing also influences greenhouse gases in the atmosphere through broader system effects, including effects on future forest carbon storage, changes in non-tree carbon pools such as dead wood and soils, and economic responses to changes in supply.

2.3.1 Forest ecosystem effects

Multiple studies have compared the carbon storage implications of various forest management systems (see, for example, Depro et al. 2008; Harmon et al. 1990; Hennigar et al. 2008; Hoover and Stout 2007; Liski et al. 2001; Luyssaert et al. 2008; Nave et al. 2010; Nunery and Keeton 2010). Effects depend upon forest type, pre-harvest stocking level, age class structure, land use history, silvicultural practice, harvest technique, and many other variables. A review of these studies is beyond the scope of this paper, but clearly harvest practice will influence forest carbon stocks and may even influence land use changes; a full life-cycle assessment should ideally incorporate any broader effects that result directly from harvest activity.

2.3.2 Economic system effects—solid wood materials substitution

Beyond ecosystem effects, changes in utilization of wood products also may affect GHG emissions through market-mediated substitution between wood and alternative materials (see Gustavson et al. 2006 for a summary of opportunities and measurement issues). In order for expanded wood use to generate GHG benefits through substitution it must: 1) replace alternative materials in the construction of final products; and 2) have lower GHG emissions than those alternatives. The potential for wood to substitute for other materials will depend on the extent to which wood is already used. In the United States, for instance,

[24] Houses were timber-frame, block, and brick and global warming potential as CO_2e was reported separately for production and construction stages. See Supplementary materials for computations.

wood is already the 'business as usual' framing technology for one- and two-family homes at 90% to 94%, while wood framing is less dominant in France at 4% and the UK at 20% (Gustavson et al. 2006).

The GHG impact of wood product substitution also depends on the relative emissions associated with wood versus the materials it replaces. Many studies have documented lower GHG profiles for wood relative to concrete and steel (Borjesson and Gustavson 2000; Nebel et al. 2006; Meil et al. 2004; Sharai-Rad and Welling 2002),[25] but comparisons to a broader range of alternatives would be helpful.

2.3.3 Economic system effects—biomass energy substitution

Biomass energy involves a special category of substitution, and is particularly relevant to wood products GHG accounting because wood processing byproducts often find their way into a boiler or furnace. Wood energy expansion alone is not sufficient to demonstrate climate benefits. Similarly to wood products, climate benefits from combustion of wood for energy depend upon: 1) the degree to which their use replaces fossil fuels, and 2) reduced carbon-intensity (GHGs released per unit of useful energy) compared to fossil fuels. Since energy facilities necessitate a flow of use over time, substitution is relatively easy to demonstrate when wood replaces fossil fuel at an existing facility with many years of service remaining. For new energy capacity, however, the difficulties of documenting substitution benefits, and identifying the alternative sources displaced, are similar to those for solid wood materials.

Aside from the difficulty of determining whether substitution has occurred and for what, previous assumptions about the carbon-neutrality of wood fuels are increasingly questioned (Johnson 2009; Searchinger et al. 2009, US EPA 2010a). In fact immediate GHG emissions from wood often exceed those from fossil alternatives (Manomet Center for Conservation Sciences 2010).[26] The excess of biomass emissions over fossil emissions for the same energy output may be irrelevant if those emissions do not represent a new release to the atmosphere, or may be partially negated if the GHGs are quickly reabsorbed. Woody fuels that may achieve low-carbon status include: 1) waste that would have decomposed and released its carbon quickly if not used for energy; 2) biomass fuel crops that regenerate quickly after each harvest and replace a land use with a lower average carbon stock; and 3) source forests that fully regenerate their pre-harvest carbon stocks (however, a lengthy recovery period gives this source a higher carbon intensity than 1) or 2)).

3 Carbon storage in wood products as a climate mitigation strategy

The remainder of this paper discusses the implications and uses of life-cycle greenhouse gas accounting for proposals to offset fossil fuel GHG emissions by increasing the use of harvested wood products. Expansion of the forest products sector as a whole will clearly

[25] These are generally 'gate-to-gate' studies that do not incorporate forest impacts within the life-cycle boundary.

[26] Prevailing technology and physical characteristics of the fuel (including higher moisture content) generally mean lower combustion efficiency and less efficient conversion to useful energy when compared with more uniform and concentrated fuels. Replacing coal with wood in an electricity generating plant with unchanged output would reduce coal emissions by only 0.66 t for every 1.00 t wood emissions, so even well-documented substitution benefits need to be discounted by an appropriate factor.

not accomplish climate mitigation goals.[27] Carbon offset programs or other subsidies require careful life-cycle accounting at an appropriate scale in order to direct incentives toward products and processes that effectively reduce GHG emissions or increase net sequestration.

3.1 Wood products and climate mitigation policy

Treatment of carbon stored in harvested products varies among international, national and voluntary project-based climate mitigation programs. Kyoto's Clean Development Mechanism has so far approved only afforestation projects in the forest category, with no accounting for harvested wood pools. To-date, the European Trading System accepts no forest offsets of any kind. The New South Wales Greenhouse Gas Abatement Scheme in Australia accepts afforestation credits but considers harvest to result in an immediate emission. In the United States, cap-and-trade bills introduced in both the House of Representatives (2009) and Senate (2009) explicitly listed wood products as integral to forest management offsets. Some voluntary carbon offset protocols also accept harvested wood products carbon as a forest offset pool (Chicago Climate Exchange 2009; Climate Action Reserve 2009; Winrock International 2010).

Variations in treatment are not surprising, as international and national climate policies are swayed by other private and public values. For instance, a cap-and-trade approach to regulating emissions, as embodied in the European Trading system and as proposed for the United States, creates new property rights for GHGs and those property rights have equity implications. In the case of regulated emitters, the right to release CO_2 into the atmosphere is defined as publicly owned and emitters must purchase that right in the form of allowances (with some perhaps allocated free-of-charge during a transition period). In the case of unregulated entities (often including forest landowners), the right to emit implicitly belongs to those entities. Offset regulations add value to those rights by declaring them equivalent to emissions from regulated entities so that they may be traded in markets. Given the emergence of new rights and new markets, various parties rationally pursue crediting conventions that add value to their own carbon rights.

Standards for forest carbon offset projects will define the carbon rights associated with wood and that definition will in turn influence the relative emphasis on accumulating carbon in forests versus accumulating carbon in furniture, homes, and landfills or burning wood to generate energy. Since offsets under a cap-and-trade policy confer new carbon property rights on some parties, such programs should be carefully designed to meet public objectives, including protecting the full suite of ecosystem services that forests provide.

3.2 Wood products and forest offset projects

Aside from equity and other broad social concerns, incorporating harvested wood carbon as a pool in forestry offset projects introduces technical complications that must be addressed to ensure accurate accounting and conservative crediting (principles established by the

[27] The United States forest products industry as a whole, including paper, released about 212 million t CO_2e in 2004–2005 from processing and transport, while these operations over the same time period increased storage in products and landfills by only 108.5 million t CO_2e (Skog et al. 2008 pp. 9 and 25). This study assumed that wood product manufacturing has no effect on forest carbon, and that wood energy used in forest products manufacturing adds no net GHGs to the atmosphere, and modifying these assumptions might increase net GHG impacts.

International Standards Organization 2006). Similar challenges arise for international projects under a post-Kyoto agreement, projects credited under national cap-and-trade climate policies, or projects offered through voluntary offset markets. Issues related to the measurement challenges outlined earlier in this article include:

Boundaries: A forest-based offset project is usually defined by geographic location. Crediting carbon after it leaves that location requires the collaboration of multiple unrelated parties whose decisions affect the amount of carbon retained. Inclusion of this pool in forest offsets will require clarifying legal rights to carbon and determining when associated emissions that are not otherwise regulated under a systematic cap must be reported as part of a project.

Measurement: Protocols typically call for periodic field sampling of forest carbon pools (Chicago Climate Exchange 2009, Climate Action Reserve 2009, Voluntary Carbon Standard 2008, Winrock International 2010). Comparable treatment for off-forest carbon would require periodic monitoring of the wood flow for each project, but this task is much more difficult than monitoring forest pools. Given the variability in wood processes illustrated in Section 2, any use of broad regional or national data for an individual project must be subject to appropriate uncertainty discounts.

Permanence: Ensuring permanent forest carbon storage usually depends upon monitoring for reversals which release credited carbon due to natural or human disturbances. Off-site wood carbon cannot be monitored in this way. Long-term storage depends upon the behavior of consumers, which is likely to change considerably over the many decades normally considered a proxy for true permanence. Likewise, crediting long-term carbon storage in landfills depends upon highly-uncertain assumptions about the fate of land-filled wood. As mentioned above, uncertainty discounts should apply when broad economy-wide averages based on past behavior and technology are used to estimate wood storage over time for a specific project.

4 Discussion and conclusion

The information summarized here indicates that storage of carbon in wood products deserves close scrutiny before it is widely adopted as a climate mitigation strategy. Not all wood products help build long-lived carbon stores, and high processing and transport emissions may undermine any gains achieved. Full and accurate accounting will ensure that offsets and other mitigation strategies produce the promised greenhouse gas benefits.

The data summarized in this article indicate that GHGs released from wood product processing, use and disposal in the United States are substantial. For the sector as a whole, as little as 1% of initial standing-tree CO_2e may remain in products in-use and 13% in landfills at 100 years post-harvest (last bar of Fig. 1). Processing and transport emissions associated with long-lived wood products may range from negligible to nearly equal to the amount of CO_2e stored in finished products (see Fig. 3 examples). Because of the significance and variability of these emissions, proposals to expand wood product use as a climate strategy must use LCA methodologies similar to those cited here, applied at an appropriate scale, to assess net GHG impacts. Broader system effects may either increase (e.g. if harvest permanently lowers forest carbon reserves) or decrease (e.g. if wood directly replaces more carbon-intensive materials or fuels) net emissions associated with wood products production, and should be included in an assessment if possible.

Considerable international effort has resulted in widely-supported methodologies for reporting the harvested wood carbon pool within national-level greenhouse gas inventories.

Yet as discussed inventories are insufficient to identify policy actions that can lower total GHG emissions; only more detailed life-cycle assessments can provide this information. Offsets or other climate mitigation proposals that use carbon accumulating in wood products and landfills to balance continuing fossil fuel emissions require complete and up-to-date life-cycle data. Beyond the need for better data, such projects also face more 'wicked' accounting challenges, including the need to show that any increases are additional to the 'business as usual' case, that associated process emissions and market leakage do not undermine carbon gains, and that carbon remains in storage for a sufficient time to deliver promised climate benefits.

Though accumulating more carbon in wood products and landfills is to some extent compatible with increasing carbon in standing forests, there is ultimately some trade-off between these approaches. The treatment of harvested wood pools in offsets and other mitigation activities will help tip the balance between these two emphases, and policy makers should consider the full range of public costs and benefits that flow from each approach. Either approach could boost revenue for landowners, providing incentives to keep forests as forests. In most cases, boosting forest carbon stocks will create self-sustaining carbon reserves, while providing co-benefits such as late-successional wildlife habitat, water regulation, and other ecosystem services; but taken to extremes this approach could reduce wood supply and drive up demand for materials with higher climate impacts. Increasing carbon storage in wood products and landfills may slow the release of GHGs from harvested wood (if the emphasis is on efficiency and product longevity rather than simply increased volume) and may help reduce GHG emissions by substituting for more fossil-fuel-intensive alternatives; but growing the harvested wood pool relies on continued fossil fuel inputs and requires space for housing and landfills that displace carbon-fixing vegetation.

National forest carbon policies will require balancing many interests and multiple forest values. Like field foresters practicing adaptive management, climate policy developers will need to proceed with caution, continually assess results, accommodate evolving science, and modify policies to best fulfill the climate mitigation potential of the forestry sector. Both positive and negative climate consequences should be considered when contemplating the expanded use of wood products as a core climate mitigation strategy.

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