The greenhouse gas and carbon profile of the global forest products industry

Reid Miner*
John Perez-Garcia

Abstract

In this paper, widely accepted calculation methods and readily available data sets are used to characterize the forest products industry's global carbon and greenhouse gas profile. The result is useful in understanding the industry's current contributions to atmospheric greenhouse gases. The global forest products industry's carbon and greenhouse gas profile is composed of emissions, sequestration, and avoided emissions. Emissions associated with forest products industry activities and products include emissions from manufacturing, as well as emissions associated with electricity purchases, transport, and releases of methane from discarded forest products in landfills. Carbon is sequestered in forests used to supply fiber to the industry and in forest products. Because the stocks of carbon in sustainably managed forests, averaged over time and area, are relatively stable, net sequestration is determined primarily by the fate of carbon transferred into products. The estimates developed in this study indicate that the greenhouse gas emissions associated with the activities and products of the global forest products industry are largely offset by sequestration, primarily attributable to increasing stocks of carbon in forest products. Avoided emissions, which represent other important connections between the industry and the global carbon cycle, are associated with the industry's use of biomass fuels, combined heat and power systems, recycling, and product substitution effects.

Strategies to reduce industrial emissions of greenhouse gases frequently focus on manufacturing emissions. Manufacturing operations, however, are only one element of the life cycle of forest products, a life cycle that includes a series of activities beginning with the production of raw materials and terminating with the end-of-life management of used products. The development of optimal greenhouse gas control policies requires an understanding of the emissions and sequestration associated with the entire life cycle of forest products. In this study, we estimate the emissions and sequestration associated with the life cycle of the products manufactured by the global forest products industry. We use the term "carbon and greenhouse gas profile" to describe the overall picture of emissions, sequestration and related activities having important implications to the industry's connections to the global carbon cycle. The boundaries of the analysis include forest growth, harvesting and regrowth, establishment of new forests, transport of raw materials, forest products manufacturing (including the use of purchased electricity), product transport, carbon stored in products, and emissions from products disposed in landfills. Several additional activities are examined in terms of the emissions that would have occurred if the industry's practices had been different (i.e., avoided emissions). The analysis does not attempt to characterize global "substitution effects," i.e., the positive or negative effects associated with substituting forest products for competing products in commerce. At the global level, it is not possible to examine substitution effects because there are too many product substitutions and too many possible scenarios to examine. Some specific product substitutions, however, (e.g., involving wood-based building products) have been widely studied and are discussed.

The forest products industry's carbon and greenhouse gas profile consists of three distinct parts—emissions, sequestration, and avoided emissions. Emissions consist of transfers of greenhouse gases to the atmosphere from forest products industry facilities or from elsewhere in the forest products life cycle. These emissions consist primarily of carbon dioxide from fossil fuel combustion and methane from decomposition of discarded products in landfills. Sequestration refers to increases in the amounts of carbon contained in forests, forest products and landfills. Avoided emissions are emissions that

The authors are, respectively, Vice President, Sustainable Manufacturing, NCASI, Research Triangle Park, North Carolina (rminer@ncasi.org) and Professor, College of Forest Resources, Univ. of Washington, Seattle, Washington (perjohm@u.washington.edu). This paper was received for publication in February 2007. Article No. 10323.
*Forest Products Society Member.

Forest Prod. J. 57(10):80-90.

did not occur because of specific industry activities. Among the avoided emissions calculated in this study are (a) the emissions from combustion of fossil fuels that would have occurred if the industry did not rely so heavily on biomass fuels and combined heat and power systems, and (b) the emissions of methane from landfills that would have occurred if paper was not recycled. Other avoided emissions (e.g., due to specific substitution effects) are examined qualitatively. In this analysis, avoided emissions are included to illustrate a number of important connections between the industry and the global carbon cycle that can be missed if looking only at calculations of emissions and sequestration. The question of whether avoided emissions should be included in greenhouse gas balance sheets is beyond the scope of this paper.

Below we examine the emissions, sequestration, and several types of avoided emissions for the global forest sector. Many of the emission aspects of the industry's greenhouse gas and carbon profile were examined by Subak and Craighill in 1999 (Subak and Craighill 1999). Since then, data and methods have evolved. More recent emissions data are available, and a number of studies have been published, allowing transportation- and downstream manufacturing-related emissions to be characterized. There have also been advances in methods and data to analyze emissions associated with the forest products component of municipal solid waste (MSW).

Sequestration analyses have improved as the Intergovernmental Panel on Climate Change (IPCC) has researched and recommended approaches to account for carbon in forests, and forest products in use and in landfills. Life cycle studies of houses have been completed in Europe, Australia, the United States and elsewhere, and have been used to examine the industry's value-added chains (e.g., in Peterson and Solberg 2003). This paper summarizes the results of applying these new data and methods to characterize the different components of the forest product industry's global greenhouse gas and carbon profile. A comprehensive description of the estimation methods is available elsewhere (NCASI 2007).

Greenhouse gas emissions from the forest products life cycle

Direct emissions from the forest products industry manufacturing facilities

Almost all of the greenhouse gas emissions from forest products industry manufacturing facilities are the result of fossil fuel combustion.[1] The U.S., Canada, Europe, Japan, and Australia represent 67 percent of global production of market pulp, paper and paperboard (FAO 2006a, Pulp and Paper 2005). Their average greenhouse gas emissions for 2002 to 2004 were 121 million metric tonnes (DOE 2002, Environment Canada 2004, CEPI 2005, 2006, JPA 2006, A3P 2005). Globally, this extrapolates to 198 million tonnes of CO_2 per year. The estimate agrees closely with a global estimate of 191 million tonnes of CO_2 per year calculated using generally accepted GHG emission factors and IEA data on sector fuel use (IEA 2006). The two can be averaged to yield an estimate of 195 million tonnes CO_2 per year.

Wood products facilities in the member countries of the Organization for Economic Cooperation and Development (OECD) produce 64.6 percent of the world's sawnwood and wood-based panels (FAO 2006a). Using International Energy Agency (IEA) data, the CO_2 emissions associated with fossil fuel at these facilities can be estimated to be 16 million tonnes CO_2 in 2004 (IEA 2006). Extrapolating the emissions from these regions to the rest of the world yields an estimate of 25 million tonnes of CO_2.

Published emission factors and fuel consumption statistics suggest that methane and nitrous oxide emissions from combustion of all fuels (on a CO_2 equivalents basis) amount to approximately 5 percent of the CO_2 emissions from fossil fuel combustion (IPCC 2006, NCASI 2005). Applying this factor increases the direct, combustion-related emissions from paper and paperboard mills to approximately 205 million tonnes of CO_2 equivalents per year. Given the uncertainty in the wood products methane and nitrous oxide emissions estimates, a 5 percent increment is considered insignificant, and therefore we ignored non-CO_2 emissions from wood products facilities yielding total emissions associated with fossil fuel of approximately 25 million tonnes per year.

Based on information from a number of corporate greenhouse gas inventories and unpublished studies of the U.S. forest products industry, we determined that methane emissions from landfills and wastewater treatment systems are unlikely to exceed 7 to 10 percent of direct, combustion-related GHG emissions. Using a value of 8.5 percent results in an estimate of approximately 20 million tonnes CO_2 equivalents per year.

Downstream manufacturing emissions can be estimated from several data sources. Department of Energy (DOE) data suggest that downstream manufacturing emissions from printing and related operations are less than 4 percent of those from the paper and paperboard industry (DOE 2005). A study of the life cycle of North American magazines found that downstream manufacturing emissions were 3 percent to 7 percent of those from pulp and paper manufacturing (Gower et al. 2006). For some types of products, there are almost no downstream manufacturing emissions, e.g., converting rolls of paper into cut sheets. Life cycle studies of houses in Europe have found that the emissions resulting from house construction (not including worker transport) are less than 10 percent of the embodied greenhouse gas emissions in the building materials (Cole 1999). Based on these sources, we assumed that secondary manufacturing operations are responsible for emissions equal to 10 percent of those from primary manufacturing, or 25 million tonnes of CO_2 equivalents per year. Half of this amount was assigned to direct emissions from manufacturing, and half of the emissions were attributed to purchased electricity.

Indirect emissions associated with purchases of electricity

We estimated emissions associated with purchased electricity for pulp and papermills to be approximately 140 million tonnes of CO_2 per year. We derived this estimate from either (a) indirect emissions estimates from national associations and national governments, or (b) data on electricity purchases, and purchased electricity emission factors that are country-specific, or multinational in the case of Europe (DOE 2002, EC 2002, A3P 2005, CEPI 2005, 2006, JPA 2006).

Wood products facilities consumed 54,184 GWh in OECD countries in 2004 (IEA 2006). Because there is relatively little power generation at wood products facilities, it is reasonable

[1] The industry also burns large quantities of biomass fuels, but the CO_2 released from biomass combustion is part of a natural cycle and is not included in greenhouse gas totals (IPCC 2006).

to assume that consumption equals purchases. Using an emission factor of 450 tonnes CO_2 per GWh, a factor that is about midway between regions heavily reliant on coal for electricity and those regions that are more reliant on hydropower and nuclear power, electricity purchases by OECD wood products facilities were estimated to account for 25 million tonnes per year of CO_2. Using the FAO data described above to extrapolate from the OECD to the globe, it is estimated that the global wood products sector's indirect emissions associated with purchased electricity amount to approximately 40 million tonnes CO_2 per year.

The wood products facility estimates were checked against estimates generated using data from the Consortium on Renewable Resources and Industrial Materials (CORRIM) studies (Lippke et al. 2004, Perez-Garcia et al. 2005, and Puettmann and Wilson 2005). Using CORRIM emissions data and FAO production data, the global wood products industry was estimated to release 59 million tonnes CO_2, combined direct emissions and indirect emissions (associated with purchased power). This compared reasonably with the 65 million tonnes of CO_2 derived by adding the direct (25) and indirect (40) emissions estimates developed above.

Emissions associated with procuring and transporting raw materials and products

The paper and paperboard sector

Transportation-related emissions can be estimated from a number of sources. A study of conditions in the North American pulp and paper industry found that tree harvesting and transport resulted in greenhouse gas emissions that were generally about 10 percent of virgin manufacturing emissions (PTF 2002). The same study found that emissions from collecting recovered paper were about 5 percent of recycled paper manufacturing emissions (direct plus indirect). A more recent study of the life cycle of paper for several North American magazines found that transportation represented 10 to 18 percent of direct emissions from the mill, or 9 percent to 14 percent of combined direct emissions and indirect emissions from purchased power (Gower et al. 2006). The International Institute for Economic Development (IIED) estimated that transport-related emissions in Europe are approximately 5 percent of the pulp and paper industry's direct and indirect manufacturing-related emissions of CO_2 (IIED 1996).

Based on these sources, we assumed that transport-related emissions equaled 10 percent of total manufacturing-related (direct and indirect) emissions resulting in an estimated 40 million tonnes CO_2 per year for the paper and paperboard sector.

The wood products sector

Using data developed by CORRIM (Puettmann and Wilson 2005) we estimated that total transport-related emissions from the wood products sector are approximately 26 million tonnes CO_2 per year assuming an average transport distance of 2500 km by rail and 60 km by road and diesel fuel usage. By comparison, Schwaiger and Zimmer (2002) found that CO_2 emissions from harvesting and transporting roundwood to the forest products industry by truck range from 6.3 to 21.7 kg CO_2 equivalents per cubic meter of roundwood depending on the country . Berg and Karjalainen (2003) suggest a similar range. Using a value of 15 kg CO_2 equivalents per cubic meter, and assuming that the wood products sector consumes one-half of the 1.7 billion cubic meters of global industrial round wood production (FAO 2006a), it is estimated that harvest and wood transport is responsible for 13 million tonnes CO_2 per year for the wood products sector globally.

To estimate emissions associated with distribution of manufactured wood products, one can use data from Petersen and Solberg (2003) and FAO production data (FAO 2006a) to estimate that global emissions are about 13 million tonnes of CO_2 per year. Adding the premanufacturing transport emissions (13 million tonnes CO_2 per year) to the wood product transport emissions (another 13 million tonnes CO_2 per year) yielded a total of approximately 26 million tonnes CO_2 per year for transport in the wood products sector, which is identical to that developed above using the CORRIM data.

Alternatively, one could assume that because the mass of wood products is about equal to the mass of pulp and paper, transport-related emissions for the two sectors should be comparable, or about 40 million tonnes CO_2 per year, a value higher than that estimated using the other approaches described above. Based on these various approaches, we determined that transport-related emissions from the wood products sector are approximately 30 million tonnes CO_2 per year.

Methane emissions attributable to forest products in landfills

We calculated methane emissions of the forest products industry's greenhouse gas profile using IPCC methods (IPCC 2003, 2006). The amounts of products discarded every year were estimated by developing a time series of carbon stocks in products-in-use to reflect each year's new production and the eventual removal from use of previously manufactured products. The time-in-use was determined using a first order decay curve and the half-life values following IPCC (2003). These calculations are described in more detail below in the discussion of carbon in products in use and in landfills and in NCASI 2007. Assumptions regarding the fraction of used forest products that are discarded in landfills were taken from IPCC (2006). Data generated by Barlaz (2004) indicate that many wood products, as well as paper products that are high in lignin or are coated, are expected to degrade to a much smaller extent than suggested by IPCC defaults (which assume that 50 percent of the organic carbon degrades to gas). This would cause the estimates for methane generation derived herein to be high.

Another very important factor affecting methane emissions estimates is the fraction of MSW landfills globally that are equipped with methane collection systems. Bognar developed estimates of global methane releases from MSW landfills assuming that 6.6 to 18.2 percent of the potential methane releases were captured and burned, but noted that these estimates were probably low by 50 to 100 percent due to underreporting of landfills that burn gas without recovering energy (Bognar 2003). As a result, for this analysis, we assumed 20 percent of potential releases were collected and burned.

These assumptions yielded an estimate of average methane emissions for the period 2000 to 2005 of approximately 250 million tonnes of CO_2 equivalents per year attributable to the decomposition of forest products in landfills. We estimated about two-thirds of this is attributable to paper products and one-third to wood products using IPCC default assumptions. If, for wood products, it is assumed that only 25 percent rather than 50 percent of the carbon is degraded under anaerobic conditions (a value comparable to findings for coated papers and newsprint in Barlaz 2004), the estimate of total releases becomes about 200 million tonnes, of which three-quarters are due to paper products rather than wood products.

A report by IIED estimated that 12 million tonnes of methane (about 250 million tonnes CO_2 equivalents) are released from paper in landfills globally each year (IIED 1996, Subak and Craighill 1999). Although the estimate reported by IIED appears to agree with the estimate derived above, it is important to note that the IIED estimate is based only on paper and paperboard whereas the estimate derived above includes wood products as well. An estimate more comparable to the IIED estimate was obtained in this study by setting the landfill degradation rate to zero for wood products. This yielded an estimate of 150 million tonnes of CO_2 equivalents attributable to paper and paperboard in landfills. In comparing the IIED estimate to the ones derived herein, it is important to consider that the two estimates were developed using very different approaches.

The results from this study were compared to estimates of global landfill methane emissions. These estimates were reported to vary from 9 to 70 million tonnes of methane, or 189 to 1470 million tonnes of CO_2 equivalents per year (Bognar 2003). The size of this range highlights the uncertainties associated with the estimates attempted above. Bognar suggests that within this range, it is most likely that global methane releases from landfills are 16 to 20 million tonnes methane (336 to 420 million tonnes CO_2 equivalents) per year (Bognar 2003).

Methane emissions from MSW landfills in the United States, the EU-15 and Japan combined amount to approximately 210 million tonnes of CO_2 equivalents (EC 2005, USEPA 2006a, and MOE 2006). According to World Bank statistics, these three regions represent approximately 40 percent to 60 percent of global gross domestic product, suggesting that an estimate of global MSW methane releases of 336 to 420 million tonnes CO_2 equivalents is not unreasonable.

Estimates for total landfill methane releases should be larger than those attributable only to forest products since landfill methane is generated from waste materials besides discarded forest products. If global methane releases from landfills are 336 to 420 million tonnes CO_2 equivalents per year, and forest products are responsible for 250 million tonnes of CO_2 equivalents per year, then decomposing forest products might be responsible for as much as two-thirds of global landfill methane emissions.

The estimate was checked against information collected in the United States. U.S. emissions of methane from MSW landfills have been reported to be 141 million metric tonnes CO_2 equivalents in 2004 (USEPA 2006a). If we assume that two-thirds of this is due to paper and wood products (as suggested by the calculations above) then about 95 million tonnes of CO_2 equivalents of methane are attributable to forest products in landfills. The U.S. accounts for approximately 30 percent of global consumption of pulp, paper and wood products (FAO 2005), and probably a larger than 30 percent share of landfilled forest products globally since relatively more paper and wood are landfilled in the United States than in many other developed countries. An estimate of 250 million tonnes of CO_2 equivalents of emissions attributable to decomposition of forest products globally, therefore, does not appear unreasonable.

Carbon sequestration in the forest products life cycle

Accounting for forest carbon

Forest biomass globally has been estimated to contain 283 billion tonnes of carbon. The global forest ecosystem as a whole, including deadwood, soils and litter, contains 683 billion tonnes of carbon (FAO 2006b). This is approximately equal to the amount of carbon in the atmosphere (IPCC 2001). The amount of carbon cycling between global forests and the atmosphere (gross primary productivity) has been estimated to be approximately 85 billion tonnes per year (WBCSD 2005). About 30 billion tonnes of the carbon removed from the atmosphere by forests per year are converted into biomass (net primary productivity), representing about one-half of the biomass production in the terrestrial environment (Sabine et al. 2004). By comparison, the amounts of carbon removed from forests by the forest products industry are small, amounting to approximately 0.30 to 0.35 billion tonnes per year (WBCSD 2005). The amounts of biomass and carbon in forests are stable or increasing in essentially all developed countries (Kauppi et al. 2006).

Given the requirements of sustainable forestry management programs to employ practices that ensure a continued supply of wood, we assumed that carbon stocks in industrial forests managed under sustainable forestry principles are, at worst, stable over time.[2] For a number of reasons, the assumption of constant forest carbon stocks likely understates the carbon benefits of sustainably managed industrial forests. Not only are some areas of managed forests set aside for environmental reasons, managed forests are also less at risk for catastrophic losses of carbon due to fire and insects. U.S. carbon stocks on private timberland [3] are increasing by more than 240 million tonnes of CO_2 equivalents per year (Bickel et al. 2004). It appears that at least one-quarter of private timberland is managed to produce wood for the forest products industry, suggesting that 60 million tonnes of forest carbon sequestration can be directly attributed to the U.S. forest products industry.[4] Significant increases in forest carbon stocks have also been reported for Europe and throughout the developed world (FAO 2005, Kauppi et al. 2006), but the data are inadequate to support an estimate of how much of this occurred on land used for wood production. Significant amounts of carbon are contained in portions of industry-owned forests that are set aside for water quality production, habitat preservation, and other environmental and conservation purposes, and these carbon stocks may be increasing. In addition, carbon is accumulating in significant areas of forest that are not managed primarily for wood production, but which provide some wood to the industry. In many cases, these forests would be cleared (and the carbon benefits lost) were it not for the income from sales to the forest products industry.

Since forest carbon stocks are stable or increasing in the countries that produce most of the world's forest products

[2] The ability of sustainable forest management practices to maintain carbon stocks has recently been recognized in the U.S. government's program for voluntary reporting of greenhouse gas emission reductions (DOE 2006).

[3] Private timberland meets minimum levels of productivity and is available for timber harvest

[4] Private timberland covers about 360 million acres in the United States (Smith et. al. 2004). The Sustainable Forestry Initiative includes about 130 million acres of certified forests (AF&PA 2006), about 50 million of which are in Canada (Abusow 2004). This leaves 80 million in the United States, which would represent one-quarter of all private timberland.

(Kauppi et al. 2006), it is reasonable to assume that globally, land managed for wood production is currently accumulating carbon at a rate at least equal to the accumulation in land managed to produce wood for the U.S. forest products industry. This amounts to 60 million tonnes CO_2 per year. At a time when global emissions are increasing, carbon sequestration in managed forests could provide important short- to intermediate-term benefits. Nonetheless, averaged over long times and areas, managed forests probably do not accumulate significant amounts of carbon.

The global forest products industry also affects global forest carbon stocks by planting new forests. Where new forests are planted on nonforestlands (i.e., afforestation) the new forest adds to stocks of carbon sequestered in global forests. Where planted forests are established by first clearing natural forests, however, there can be a net decline in the carbon stored on the affected land area since planted forests managed for wood production often store less carbon than natural forests.

At least one study has suggested that the net effect of establishing new managed forests has been to increase global stocks of sequestered carbon. Subak and Craighill (1999) examined the carbon gained through establishing new plantations as well as the carbon lost due to conversion of natural forests to plantations. They estimated the balance to be net sequestration of 158 million tonnes CO_2 per year although it was noted that the estimate was subject to considerable uncertainty.

Estimating the net effects of new forest establishment at the global level is difficult. There is great variability in forest carbon stocks, even within a single region and the impacts on soil carbon are complex. Available data indicate that during the 1990s, the land area converted from natural forest to planted forest was approximately equal to the land area converted from non-forest to planted forest (FAO 2001). Considering the likely impacts of these changes on carbon, it appears reasonable to conclude that, at worst, during the 1990s, the loss of carbon on natural forestland converted to planted forest was approximately offset by the increase in carbon stocks on non-forestland that was converted to planted forest. Again, this finding is subject to considerable uncertainty.

Finally, it is also necessary to consider the potential impacts of converting forestland to non-forestland; i.e., deforestation. While carbon stocks in European and North American forests are stable or increasing, those in Africa, Asia and South America are declining (FAO 2006b), mostly due to deforestation. The causes of deforestation are complex and vary from one location to another, but at the global scale, deforestation is "mainly due to conversion of forests to agricultural land . . . " (FAO 2006b). The differences between countries accumulating forest biomass and countries losing forest biomass are not related to the size of the harvest, but rather to population density and income per capita with poor countries having high population densities being most at risk for deforestation. (Uusivuori et al. 2002, Kauppi et al. 2006) These and other studies indicate that the forest products industry, especially with respect to corporations using sustainable forest management practices, is not a significant contributor to carbon losses associated with deforestation.

Sequestration in forest products in use

After manufacturing, forests products remain in use for periods varying from days to centuries. During this period, the carbon remains sequestered, delaying its return to the atmosphere. If carbon in products is being added to the in-use pool faster than it is being removed by the retirement of previously manufactured products, the stocks of carbon in the products-in-use pool will grow.

Stocks of carbon in products-in-use were estimated using FAO data and IPCC methods and, in most cases, default parameters recommended by IPCC. The expected times-in-use for various types of forest products were described using IPCC's first order equation method (IPCC 2006) and IPCC half-lives that vary by product type (IPCC 2003). Stocks of carbon in products-in-use were estimated for the period 1900 to 2005. The annual growth in the stocks of carbon in products-in-use averaged 55.4 million tonnes of carbon (approximately 200 million tonnes of carbon dioxide equivalents) per year between 2000 and 2005.

Pingoud et al. (2003) estimated that, in the late 1990s, global stocks of carbon in products-in-use were growing at approximately 35 million tons of carbon per year, a value 35 percent lower than the estimate developed in this analysis (UNFCCC 2003). It appears that the estimate developed herein is larger than the Pingoud estimate primarily due to the use of lower product half-lives in the Pingoud study, although some of the difference may be due to increased production in the post-2000 period.

The global estimate derived herein can also be compared to the estimates in the U.S. inventory of greenhouse gas emissions. EPA reports that the pool of carbon in products-in-use attributable to U.S. production, is growing at a rate of 44 million tonnes CO_2 equivalents per year, an amount equal to one-quarter to one-fifth of the amount estimated herein for the globe (USEPA 2007). The United States produces about one-quarter of global output of sawnwood, paper, and paperboard products (FAO 2005), suggesting that the global estimate derived above is reasonable.

Sequestration in forest products in landfills

After use, products are recycled or discarded. The end-of-life management of waste materials varies greatly among countries and even within countries. In most countries, however, some of the discards are placed in landfills. In many cases, these landfills are anaerobic, which provides an environment wherein many forest products decay only slowly, if at all. As a result, the amounts of carbon in MSW landfills are increasing with time.

Accounting for the carbon remaining in landfills involves developing a landfill mass balance for carbon. The carbon in new discards to landfills is netted against carbon lost in gas, both in methane and carbon dioxide. If the losses of carbon in gas are smaller than the carbon in new discards, the stocks of carbon in the landfills are growing. Using estimates of discards derived from the calculations for products-in-use and landfill decay calculations described above, it is estimated that from 2000 to 2005, the stocks of carbon in forest products in landfills were increasing by an average of 92 million tonnes of carbon (approximately 340 tonnes of carbon dioxide equivalents) per year.

In this assessment, landfill methane emissions attributable to paper and wood products (250 million tonnes CO_2 equivalents per year) are approximately offset by net sequestration attributable to those same products (340 million tonnes CO_2 equivalents per year). This finding is similar to that found in a study of forest products and waste management in Finland (Pingoud et al. 1996).

Avoided emissions associated with the forest products life cycle

Avoided emissions are those that would have occurred in the absence of an activity. Avoided emissions are fundamentally different from the other components of the industry's profile (described above). Direct emissions, indirect emissions and movements of forest carbon into and out of the atmosphere are measurable. They do not require assumptions about alternative activities or speculation about what might have happened if things had been done differently. Avoided emissions, on the other hand, represent what might have happened if things had been done differently.

Estimates of avoided emissions are inherently uncertain because they require assumptions about events that would have occurred were it not for activities that are in place or assumed to occur under business-as-usual conditions. Uncertainty notwithstanding, avoided emissions estimates can provide insights into important attributes of the forest products industry's carbon and greenhouse gas profile and the public policies that influence it. The question of whether avoided emissions should be included in greenhouse gas balance sheets is beyond the scope of this paper.

Sixty-three percent of the fuel used by the wood products industry and 49 percent of the fuel used by the pulp and paper industry is biomass-derived (WBCSD 2005). This is far more than any other major industry. When these fuels are burned, they return carbon to the atmosphere that was only recently removed from the atmosphere. As a result, biomass fuels are carbon-neutral. In contrast, fossil fuels put carbon into the atmosphere that has not resided there for millions of years, causing increases in atmospheric CO_2 levels. If the forest products industry used fossil fuels to satisfy the energy needs now satisfied by biomass fuels, its net direct emissions would be significantly larger. Assuming one-half of the fuel used by the forest products industry is biomass-derived and assuming that one MJ of fossil fuel produces as much usable energy as 1.25 MJ of biomass fuel, the approximate magnitude of these avoided emissions is estimated to be approximately 175 million tonnes of CO_2 per year.

Combined heat and power, or CHP, systems involve the sequential use of steam to produce electricity and then heat, usually in steam that is used in pulping and paper-making processes. CHP systems extract far more usable energy from fuels compared to systems that produce steam and electricity separately. USEPA indicates that CHP systems typically increase overall efficiencies by perhaps 50 percent and reduce fuel requirements by 35 percent (USEPA 2006b). CEPI has estimated that the CHP systems in the European pulp and paper industry allow energy savings of 30 to 35 percent (CEPI 2005). Assuming a scenario representing the industry's activities in the absence of CHP systems, where the industry would cease producing electricity and instead would purchase all electricity needed by the industry, leads to greater indirect emissions associated with purchased electricity.

The European paper industry produces about 46 percent of its net electricity consumption. Since approximately 93 percent of this is produced in CHP systems, about 43 percent of net consumption is produced in CHP systems (CEPI 2005, 2006). In the United States, approximately 89 percent of the electricity generated by pulp and papermills is generated in CHP systems, representing 40 percent of net electricity consumption (DOE 2002). Using the lower of the two values (40%), we estimated that electricity purchases and the associated indirect emissions from pulp and papermills would increase by 67 percent (= 40/60) if CHP systems were not used. This increase amounts to approximately 95 million tonnes CO_2 per year in avoided indirect emissions associated with purchased power.

The effects of paper recycling on carbon and greenhouse gases are complex. Paper recycling can keep discarded paper out of MSW landfills, where it would decay, resulting in the release of methane. On the other hand, if the alternative to recycling is burning for energy, recycling can eliminate the opportunity to displace fossil fuel with a biomass energy source. In either case, keeping carbon out of landfills also eliminates carbon sequestration in landfills. The interactions between avoided methane emissions, displaced fossil fuel emissions from burning used paper (or landfill methane), and forgone landfill carbon sequestration are highly grade- and site-dependent.

Furthermore, recycling mills sometimes release more greenhouse gases than virgin mills since recycling mills have less access to biomass fuels and are less likely to have equipment that is readily suited to burning them for energy. The differences in these direct emissions, however, are extremely dependent on the grades of paper being considered.

Recycling also reduces the need for virgin pulpwood fiber, potentially allowing additional carbon sequestration in the forest. The effects of recycling on forest carbon, however, are not as straightforward as sometimes thought. Activities that reduce the demand for virgin fiber can increase the chances that land will be converted from forests to other uses, resulting in the loss of large amounts of carbon. Or a loss in demand for pulpwood may result in a decision to delay harvesting only until the trees become large enough to be used as sawtimber, at which point the harvesting eliminates some of the sequestration in the forest but adds to sequestration in long-lived building products. The factors that affect the impacts of recycling on forest carbon are complex and difficult to quantify but can be important.

The authors are aware of only one study that attempts to deal with most of these factors. A study by USEPA suggests that, even considering these various factors, recycling can have carbon and greenhouse gas benefits (USEPA 2002). The impacts are highly grade-specific, however. In addition, the results would be very different in a setting where waste management practices are different from those in the United States. Based on current studies, it appears that in many cases and at current recycling rates, paper recycling helps avoid life-cycle emissions of greenhouse gases (although there are exceptions).

As noted earlier, by using the methods for estimating landfill methane emissions, and setting the assumed degradation rate for wood products to zero, we determined that paper and paperboard products were responsible for 150 million of the 250 million tonnes CO_2 equivalents of methane emissions attributable to forest products in landfills. Of the 352 million tonnes of paper and paperboard produced globally in 2005, 162 million tonnes, or 46 percent, was recovered rather than being disposed (FAO 2006a). Accordingly, the methane emissions attributable to paper and paperboard in landfills would approximately double if the paper currently recovered was disposed instead. The resulting estimate of avoided emissions attributable to paper recycling is, therefore, 150 million tonnes CO_2 equivalents per year, an estimate that admittedly does not consider the various complexities noted above.

Forest products compete in the marketplace with alternative products that often have very different greenhouse gas and carbon profiles. As a result, when forest products either displace, or are displaced by, other products, there can be effects on global greenhouse gas emissions. These "substitution effects" are very product specific. Even for a single type of product, substitution effects will vary according to local conditions.

In the case of building products, a number of studies have found that for residential structures with comparable heating and cooling requirements, wood-based structures usually have lower life cycle greenhouse gas emissions than many alternative structures. See, for instance, Richter and Sell 1993, Peirquet et al. 1998, Borjesson and Gustavsson 2000, Scharai-Rad and Welling 2002, Lenzen and Treloar 2002, Athena 2004, Gustavsson and Sathre 2006, Gustavsson et al. 2006, NCASI 2006, and the CORRIM studies described in Lippke et al. 2004, Perez-Garcia et al. 2005, and Puettmann and Wilson 2005. In the U.S. alone, the use of wood-based construction in the walls of single-family homes avoids an estimated 9.6 million tons of CO_2 emissions per year (NCASI 2006). The size of the impact, however, can vary greatly depending on a number of factors including assumptions about end-of-life management (Borjesson and Gustavsson 2000), and about forest carbon impacts (Gustavsson et al. 2006, NCASI 2006). Local climate will also affect the potential advantages of wood-based building materials.

The results for other types of products, however, can be very different and are affected by local conditions (e.g., waste management practices, sources of electrical power, etc.). The number of potential substitution effects and the number of local conditions that affect them are too numerous to contemplate. It was not possible, therefore, to generate a meaningful estimate of global avoided emissions due to substitution effects for this study. It is important to remember, however, that these effects can be considerable for specific products and circumstances.

There is a large number of other avoided emissions that can be identified in the forest products life cycle. Some of these are listed here without any attempt to estimate their significance:

- The use of nonrecyclable paper as biomass fuel, displacing fossil fuel
- The use of landfill-derived methane as biomass fuel, displacing fossil fuel
- The forest clearing that is avoided because the industry provides a market for wood

Discussion of the carbon and greenhouse gas profile of the forest products industry

The size of the individual components of the industry's greenhouse gas and carbon profile, and the relative uncertainties, based on the authors' judgment, are summarized in **Table 1**. The table clearly illustrates the many complex and important connections of the forest products industry to the climate change issue.

Direct emissions are an important part of the industry's global profile, estimated to be 262 million metric tonnes per year of CO_2 equivalents per year. These emissions would be greater by as much as 175 million metric tonnes of CO_2 per year were it not for the industry's use of biomass fuels. The industry in a number of regions has identified opportunities for further improvement in this area. The European paper industry, for instance, has a target of increasing average use of biomass from 49 percent to 56 percent of on-site total primary energy consumption by 2010 (CEPI 2003).

In most parts of the world, the forest products industry's direct emissions intensity (i.e., direct emissions per ton of production) has improved over the years. This has been accomplished by improving energy efficiency and substituting biomass fuels for fossil fuels. In Europe, absolute emissions have increased even though emissions intensity has improved (CEPI 2005). In Canada, on the other hand, emissions intensity since 1990 has improved faster than production has grown, providing reductions in both emissions intensity and absolute emissions (FPAC 2006). Absent major technological breakthroughs, it is reasonable to assume that the industry's emissions intensity will continue to improve at about the same rate as production growth, allowing the industry's direct emissions to remain constant.

A number of factors will affect the industry's ability to continue to improve direct emissions intensity. First, fossil fuel prices have increased dramatically in recent years, providing an added incentive for conserving energy and increasing use of biomass fuels (although the availability of relatively cheap coal and the cost of biomass may complicate attempts to forecast emission trends). The industry's ability to increase use of biomass as a raw material and fuel will depend on the continued availability of adequate supplies of affordable wood fiber. In some regions of the world, supplies of forest biomass appear to be adequate to support the forest products industry and allow significant growth in the use of forest biomass-based fuels. In other regions, however, concerns have already developed over competition for wood fiber caused by incentives to produce biomass-based electricity, illustrating the need for balanced public policies that do not distort the market for forest biomass.

Indirect emissions associated with purchased electricity are a significant component of the industry's greenhouse gas profile, amounting to an estimated 193 million metric tonnes CO_2 per year. The industry's demonstrated ability to use CHP to avoid, at present, approximately 95 million metric tonnes of CO_2 per year, suggests the value of policies to encourage expanded use of CHP in the industry. In addition, as electricity prices increase, mills may have additional incentives to produce, rather than purchase, electricity. It is also important, however, to consider the effects of energy conservation on electricity production. The primary effect of improving energy efficiency in a pulp and papermill is usually to reduce the demand for process steam. Since less steam is needed, less is available for producing electricity via CHP.

Indirect emissions are also affected by the practices of companies selling electricity to the forest products industry. Power producers may have incentives in the future to reduce the emissions intensity of the power they produce, although this is not guaranteed since some experts are predicting increased use of coal for power production in many parts of the world. Without a change in the carbon intensity of purchased

Table 1. — *Summary of the greenhouse gas and carbon profile of the global forest products industry.*

		Million tonnes CO_2 equivalents per year [a]	Degree of uncertainty (authors' judgment)
Direct emissions	Fuel consumption at pulp and papermills	205	+/− 15%
	Fuel consumption at wood products facilities	25	+/− 25%
	Management of mill wastes	20	+/− 25%
	Secondary manufacturing operations (i.e., converting primary products into final products)	12	+/− 50%
	Total direct emissions	262	+/− 20%
Indirect emissions	Electricity purchases by pulp and papermills	140	+/− 25%
	Electricity purchases by wood products facilities	40	+/− 50%
	Electricity purchases by secondary manufacturing operations (i.e., converting primary products into final products)	13	+/− 50%
	Harvest and transport emissions from the pulp and paper value chain	40	+/− 50%
	Harvest and transport emissions from the wood products value chain	30	+/− 50%
	Methane emissions from forest products decomposition in anaerobic municipal solid waste landfills	250	−50% to +100%
	Total indirect emissions	513	+/− 50%
Sequestration	Sequestration in sustainably managed forests	−60	+/− a factor of 2 or more
	Sequestration resulting from establishment of new managed forests	0	+/− several hundred million tonnes sequestration per year
	Sequestration in products in use	−200	+/− 50%
	Sequestration in products in landfills	−340	+/− 50%
	Total sequestration	−600	−50% to + several hundred million tonnes sequestration per year
Avoided Emissions[b]	Avoided direct emissions associated with the use of biomass fuels	−175	+/− a factor of 2
	Avoided indirect emissions related to the use of combined heat and power systems	−95	+/− a factor of 2
	Avoided indirect emissions associated with recycling paper	−150	More than +/− a factor of 2
	Avoided indirect emissions associated with product substitution effects	?	?

[a]Negative emissions indicates net sequestration

[b]Avoided emissions are included to illustrate a number of important interactions between the forest products industry and the global carbon cycle. The question of whether avoided emissions should be included in greenhouse gas balance sheets is beyond the scope of this paper.

power, it seems unlikely that the indirect emissions associated with electricity purchased by the forest products industry will decline.

At the global level, transportation-related emissions, estimated to be 70 million metric tonnes CO_2 per year, are not a dominant feature of the forest product industry's greenhouse gas and carbon profile. For specific products or companies, however, these emissions can be significant, so they cannot be ignored. In addition, the continued globalization of the industry and the trend to move production from consuming countries to low-cost regions that are distant from major markets suggest that transportation-related emissions will become more important to the industry's greenhouse gas and carbon profile in the future.

In spite of the uncertainties in the estimates, it is clear that at the global level methane emissions from MSW landfills are a significant feature of the industry's greenhouse gas and carbon profile, although their significance will vary greatly among regions depending on paper recovery and waste management practices. In this study, it is estimated that 250 million tonnes CO_2 equivalents per year are released from landfills as the result of the decomposition of forest products. The industry's paper recycling activities are estimated to avoid releases of methane equal to 150 million tonnes of CO_2 equivalents per year. Methane emissions are large primarily because of (a) economic forces and public policies that result in many used forest products being disposed in MSW landfills, and (b) the still modest extent of use of systems to capture and burn landfill methane. Both of these factors are outside of the industry's control. Current trends in waste management, however, give reason for hope that landfill methane emissions attributable to discarded forest products will decrease over time. In 2003, MSW methane emissions in the EU-15 had been reduced by 36 percent compared to 1990 (EC 2005). In the U.S., landfill methane emissions decreased by 18 percent between 1990 and 2004 while in Japan the reduction was 34 percent (USEPA 2006a, MOE 2006). It is reasonable to project, therefore, that over time, methane from MSW landfills will become a less important feature of the forest product industry's greenhouse gas and carbon profile.

On balance, the methane emissions from landfills attributable to forest products approximately balance the net sequestration of carbon in forest products deposited in landfills. This overall balance, however, obscures the different effects of different types of forest products. The available information suggests that most of the methane is likely attributable to products that are low in lignin, are uncoated, or are otherwise unprotected against microbial attack. On the other hand, most of the sequestration in landfills is likely due to materials that are high in lignin (e.g., wood and newsprint) or are in a physical form that discourages microbial attack (e.g., pieces of solid lumber or coated papers).

In this study, total life-cycle emissions are estimated to be approximately 775 million metric tonnes of CO_2 equivalents per year, although there is considerable uncertainty in this estimate due to uncertainty in the amounts of methane attributable to the decomposition of forest products in landfills. These emissions are comprised of direct emissions (34%), indirect emissions associated with purchased power (25%), transportation-related emissions (9%) and methane from forest products in MSW landfills (32%). Adding up direct emissions and emissions related to purchased power, one finds that 59 percent of the life-cycle emissions are manufacturing-related.

The sequestration benefits of the forest products life cycle are large. Over long periods of time and large land areas, it is not expected that managed forestlands will accumulate significant amounts of carbon, although at the current time, managed forests appear to be accumulating carbon. In this study, an estimate for net sequestration in managed forests is used that includes only documented sequestration on a fraction of private timberland in the United States, amounting to 60 million tonnes CO_2 equivalents per year. On a global basis, net sequestration on managed land may be significantly higher than this.

The net sequestration in forest products, in use and in landfills, is estimated to be the equivalent of 540 million tonnes of CO_2 per year. The carbon stored in forest products is extremely important to the carbon profile of the forest products industry and this carbon will almost certainly become even more important over time as consumption of forest products increases due to growing global population and increasing standards of living.

Thus, total net annual carbon sequestration throughout the forest products life cycle is estimated to be at least 600 million tonnes CO_2 equivalents per year. Considering the uncertainty in the estimates, this sequestration is in approximate balance with the emissions that occur throughout the forest products life cycle (775 million metric tonnes CO_2 per year). It is expected that this balance will continue to improve in coming years because of (a) continuing reductions in direct emissions intensity of manufacturing, (b) likely reductions in the carbon intensity of purchased power, (c) expanded efforts to keep degradable materials out of landfills and to capture and destroy landfill methane, and (d) increasing carbon sequestration in products due to increasing population and standards of living.

The carbon and greenhouse gas benefits of product substitution are highly variable and extremely difficult, if not impossible, to estimate at the global level. They should not be ignored, however, because, it may be possible to estimate the effects of product substitution at the regional or local level, and these effects can be significant, as has been documented in many studies of wood-based building products.

In 1999, Subak and Craighill examined the carbon and greenhouse gas profile of the global paper industry (Subak and Craighill 1999) and their estimates were used extensively by IIED in its report, "Towards a Sustainable Paper Cycle" (IIED 1996). Because the current study covers the global forest products industry (paper and wood products) while the Subak and Craighill study covered only the paper industry, a direct comparison of the individual estimates from the two studies is not possible for most of the components of the profile.

Perhaps the most important differences between the two studies are related to carbon in products. Subak and Craighill did not examine the effects of carbon in products while in this study we used IPCC accounting methods to examine this feature of the industry's global profile. The results indicate that the equivalent of 540 million metric tonnes per year of CO_2 is sequestered in forest products in use and in landfills. Over very long periods, most of this carbon will return to the atmosphere, but for the foreseeable future (perhaps centuries), carbon will be added to the pool of carbon in products at rate that greatly exceeds the rate at which it returns to the atmosphere. This is expected because global demand for products is increasing in response to improving standards of living and increasing global population.

The differences between the scopes of the two studies result in the studies coming to somewhat different conclusions. Subak and Craighill conclude that the global paper industry is a net emitter of greenhouse gases while this study suggests that, considering the uncertainty in the estimates, the global forest product industry's emissions are largely, and perhaps entirely, offset by carbon sequestration. Furthermore, this study suggests that it is likely that sequestration will become larger while life-cycle emissions will diminish. To appreciate the attributes of the industry's profile, this study also suggests that it is important to understand the avoided emissions related to biomass use, combined heat and power systems, paper recycling, and substitution effects, especially for wood-based building products.

Conclusions

The industry's carbon and greenhouse gas profile is composed of emissions, sequestration and avoided emissions. Global life-cycle emissions associated with forest products are comprised of direct emissions (260 million metric tonnes CO_2 per year), indirect emissions associated with electricity purchases (190 million metric tonnes CO_2 per year), harvest- and transport-related emissions (70 million metric tonnes CO_2 per year) and methane from discarded forest products in landfills (250 million metric tonnes CO_2 equivalents per year). Carbon is sequestered in managed forests (net increases equivalent to at least 60 million tonnes CO_2 per year) and forest products (540 million tonnes CO_2 equivalents per year). Avoided emissions, which represent other important interactions between the forest products industry and the global carbon cycle, are associated with the industry's use of biomass fuels, combined heat and power, recycling, and product substitution effects. The available data demonstrate that, at the global level, the greenhouse gas emissions associated with the forest products life cycle are largely offset by the sequestration accomplished in forests and forest products.

Because of data gaps and uncertainties in the estimates, especially as regards carbon in forests and methane emissions from landfills, it is not clear whether sequestration is somewhat larger than, or somewhat smaller than, life-cycle emissions. Additional work is needed to reduce the uncertainties in the estimates at several points in the life cycle. The uncertainties are especially large for (a) transportation-related emissions, (b) carbon sequestration in land owned, controlled or managed by the industry, and (c) methane emissions attributable to decomposition of forest products in landfills.

The global life-cycle emissions from forest products are expected to decline slowly over time as increases in emissions related to production growth are offset by improvements in the emissions intensity of manufacturing and reductions in methane releases from landfills. Sequestration, especially in products, is expected to become an even more important of the industry's profile as demand for products increases because of population growth and increasing standards of living. If this growth also involves the substitution of wood-based products for more greenhouse gas-intensive products, significant benefits may occur via avoided emissions.

Improvements in the industry's greenhouse gas and carbon profile will require a combination of industry activities and public policies. Industry can assist by reducing the use of fossil fuels and electricity through energy efficiency improvements and increased use of biomass. This will require industry investments and public policies that ensure the continued availability of adequate supplies of affordable biomass for use as raw material and fuel. Public policies directed at sectors outside of the forest products industry will play a large role in several critical areas. Policies that minimize the use of landfills for disposing of easily degradable forest products will continue to be important, as will policies that encourage the use of landfills designed and operated to minimize releases of methane. Also helpful will be policies that encourage additional use of CHP and provide new opportunities for exporting biomass-derived electricity to the grid. Finally, where substitution effects are found to be important, public policies that promote the use of the least greenhouse-gas intensive products may be appropriate.

Literature cited

A3P. 2005. Australian Pap. Industry Production Statistics 2003-04. Australian Plantation Products and Pap. Industry Council. Canberra, Australia www.a3p.asn.au/assets/pdf/A3P%20Paper%20Statistics%202003-04.pdf

Abusow, K. 2004. Canadian Forest Management Certification Status Rept.: Summary. Certification Summary for Canada. Abusow Inter. Ltd., Ottawa, ON, Canada. www.fpac.ca/en/pdfs/canadian_certification_summary_status_report_E.pdf

AF&PA. 2006. Sustainability and the forest products industry. American Forest & Paper Associaiton. Washington, D.C.

Athena. 2004. Comparative environmental impact assessment. *In*: Energy and the environment in residential construction. Athena Sustainable Materials Inst. Sustainable Building Series, No. 1. Canadian Wood Council. www.cwc.ca. Accessed June 4, 2005.

Barlaz, M.A. 2004. Critical Review of Forest Products Decomposition in Municipal Solid Waste Landfills. NCASI Tech. Bulletin No. 872, March 2004. www.ncasi.org/programs/areas/climate/footprint.aspx.

Berg, S. and T. Karjalainen. 2003. Comparison of greenhouse gas emissions from forest operations in Finland and Sweden. Forestry, Vol. 76, No. 3, Inst. of Chartered Foresters. Edinburgh, 2003

Bickel, K., J. Brenner, J. Duffienld, R. Follett, L. Heath, J. Kimble, D. Kruger, J. Mangino, A. Mosier, S. Ogle, K. Paustian, H. Shapouri, J. Smith, T. Wirth, and P. Woodbury. 2004. U.S. agriculture and forestry greenhouse gas inventory: 1990-2001. Tech. Bulletin No. 1907. USDA, Global Change Program Office, Office of the Chief Economist. Washington, D.C.

Bognar, J. 2003. Global methane emissions from landfills: New methodology and annual estimates 1980-1996. Global Biogeochem. Cycles 17(2):34-1–34-18.

Borjesson, P. and L. Gustavsson. 2000. Greenhouse gas balanced in building construction: Wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy 28:575-588.

CEPI. 2003. Declaration of Intent on Renewable Energy Sources. Confederation of European Pap. Industries. Brussels, Belgium.

CEPI. 2005. CEPI Sustainability Rept. Confederation of European Pap. Industries. Brussels, Belgium. www.cepi.org/files/Sustainablity%2005-173317A.pdf.

CEPI. 2006. Annual statistics 2005; European Pulp and Pap. Industry. Confederation of European Pap. Industries, Brussels, Belgium. www.cepi.org/files/Cepi%20Stats05%20final-115558A.pdf.

Cole, R.J. 1999. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Building and Environment 34:335-348. Elsevier Sci. Ltd.

DOE. 2002. Energy Information Administration Manufacturing Energy Consumption Survey (MECS) 2002. U.S. Dept. of Energy, Washington D.C. www.eia.doe.gov/emeu/mecs/contents.html.

DOE. 2005. Energy Information Administration Annual Energy Review 2005. Table 12.4. U.S. Dept. of Energy, Washington D.C. www.eia.doe.gov/emeu/aer/pdf/pages/sec12_9.pdf.

DOE. 2006. Guidelines for voluntary greenhouse gas reporting: Final rule. Federal Register, Vol. 71, No. 77, United States Dept. of Energy, Washington D.C.

Environment Canada. 2004. Canada's Greenhouse gas inventory 1990-2003. Environment Canada. www.ec.gc.ca/pdb/ghg/inventory_report/2003_report/toc_e.cfm.

EC. 2002. Commission Decision of 4 September 2002 establishing revised ecological criteria for the award of the community eco-label to copying andgraphic paper and amending Decision 1999/554/EC. Official J. of the European Communities. European Commission, Brussels, Belgium.

EC. 2005. Annual European Community greenhouse gas inventory 1990-2003 and inventory report. European Commission, Brussels, Belguim. http://reports.eea.europa.eu/technical_report_2005_4/en.

FAO. 2001. Global forest resources assessment 2000. United Nations Food and Agriculture Organization, Rome, Italy. Available at http://faostat.fao.org.

FAO. 2005. Trends in wood products: 1961-2003, United Nations Food and Agriculture Organization, Rome, Italy.

FAO. 2006a. FAOSTAT Forest Products data base. United Nations Food and Agriculture Organization, Rome, Italy. http://faostat.fao.org.

FAO. 2006b. Global forest resources assessment 2005. United Nations Food and Agriculture Organization, Rome, Italy. http://faostat.fao.org.

FPAC. 2006. 2005 Annual Review: Transformation. Forest Products Assoc. of Canada. Ottawa, Canada.

Gower, S.T., A. McKeon-Ruediger, A. Reitter, M. Bradley, D. Refkin, T. Tollefson, F.J. Souba, A. Taup, L. Embury-Williams, S. Schiavone, J. Weinbauer, A.C. Janetos, and R. Jarvis. 2006 Following the paper trail—The impact of magazine and dimensional lumber production on greenhouse gas emissions: A case study, published by the H. John Heinz III Center for Sci., Washington D.C.

Gustavsson, L. and R. Sathre. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Building and Environment 41:940-951.

__________, K. Pingoud, and R. Sathre. 2006. Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings. Mitigation and Adaptation Strategies for Global Change. Volume 11, Number 3. Springer, Netherlands.

IEA. 2006. Energy statistics of OECD countries; 2003-2004. Inter. Energy Agency, Paris, France.

IIED. 1996. Towards a sustainable paper cycle. Inter. Inst. for Environment an Development. London.

IPCC. 2001. Climate Change 2001 - The Third Assessment Rept. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventory Program. Cambridge Univ. Press. www.grida.no/climate/ipcc_tar/.

IPCC. 2003. Good practice guidance for land use, land use change and forestry. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventory Program. www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm.

IPCC. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change. Pre-publication release.

JPA. 2006. Personal communications with Japan Pap. Assoc., July 2006.

Kauppi, P., J. Ausubel, J. Fang, A. Mather, R. Sedjo, and P. Waggoner. 2006. Returning forests analyzed with the forest identity. *In*: Proc. of the National Academy of Sciences of the United States of America. Vol. 103 No. 46.

Lenzen, M. and G. Treloar. 2002. Rejoinder to: Greenhouse gas balanced in building construction: Wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy 30:249-255.

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.

MOE. 2006. National Greenhouse Gas Inventory Rept. of Japan. Ministry of the Environment, Japan. Greenhouse Gas Inventory Office of Japan. www-gio.nies.go.jp/aboutghg/nir/2006/NIR_JPN_2006_E.pdf.

NCASI. 2005. Calculation tools for estimating greenhouse gas emissions from pulp and paper mills. National Council of the Pap. Industry for Air and Stream Improvement, Inc., Published under the World Resources Inst. and World Business Council for Sustainable Development Greenhouse Gas Protocol Initiative. www.ghgprotocol.org.

NCASI. 2006. Energy and greenhouse gas impacts of substituting wood products for non-wood alternatives in residential construction in the United States. Tech. Bulletin No. 925. National Council for Air and Stream Improvement, Inc., Res. Triangle Park, North Carolina.

NCASI. 2007. The greenhouse gas and carbon profile of the global forest products industry, NCASI Special Rept. 07-02. National Council of the Pap. Industry for Air and Stream Improvement, Inc., Res. Triangle Park, North Carolina.

Perez-Garcia, J., B. Lippke, D. Briggs, J. Wilson, J. Bowyer, and J. Meil. 2005. The environmental performance of renewable building materials in the context of residential construction. Wood and Fiber Science Corrim Special Issue 37:3-17.

Puettmann, M. and J. Wilson. 2005. Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials. Wood and Fiber Science Corrim Special Issue 37:18-29.

Peirquet, P., J. Bowyer, and P. Huelman. 1998. Thermal performance and embodied energy of cold climate wall systems. Forest Prod. J. 48(6):53-60.

Petersen, A.K. and B. Solberg. 2003. Substitution between floor constructions in wood and natural stone: Comparison of energy consumption, greenhouse gas emissions and costs over the life cycle. Can. J. Forest Res. 33:1061-1075. NRC Canada, Ottawa.

Pingoud, K., I. Savolainen, and H. Seppala. 1996. Greenhouse impact of the Finish forest sector including forest products and waste management. Ambio. Vol. 25, No. 5, Royal Swedish Academy of Sciences.

__________, A. Perala, S. Soimakallio, and A. Pussinen. 2003. Greenhouse gas impacts of harvested wood products: Evaluation and development of methods. VTT Res. Notes 2189, VTT Tech. Res. Centre of Finland, Espoo, Finland.

Pulp and Paper. 2005. Market pulp expected to see price pressure on new capacity. Pulp and Pap. pp. 13.

PTF. 2002. Lifecycle environmental comparison; Virgin paper and recycled paper-based systems. The Pap. Task Force and Environmental Defense, New York. www.environmentaldefense.org/pdf.cfm?ContentID=1618&FileName=WP3%2Epdf.

Richter, K. and J. Sell. 1993. Life-cycle analysis: A useful approach to promote wood as a construction material. Wood Focus Design summer 1993:14-17.

Sabine, C.L., M. Heiman, P. Artaxo, D.C.E. Bakker, C.-T.A. Chen, C.B. Field, N. Gruber, C. LeQuéré, R.G. Prinn, J.E. Richey, P. Romero-Lankao, J.A. Sathaye, and R. Valentini. 2004. Current status and past trends of the carbon cycle. The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. C.B. Field and M.R. Raupach, eds. Island Press, Washington, D.C. pp. 17-44.

Scharai-Rad, M. and J. Welling. 2002. Environmental and energy balances of wood products and substitutes. Food and Agriculture Organization of the United Nations (FAO). www.fao.org.

Schwaiger, H. and B. Zimmer. 2002. A comparison of fuel consumption and GHG emissions from forest operations in Europe. Results of Task 4, Working Group 1 (Production) in the COST Action E9: Life Cycle Assessment of Forestry and Forest Products. Joanneum Res. Inst. Graz, Austria.

Smith, B.W., P.D. Miles, J.S. Vissage, and S.A. Pugh. 2004. Forest Resources of the United States: 2002. North Central Res. Sta., USDA Forest Serv., St. Paul, Minnesota.

Subak, S. and A. Craighill. 1999. The contribution of the paper cycle to global warming. Mitigation and Adaptation for Global Change, Vol 4. Kluwer Academic publishers, Belguim. pp. 113-135.

UNFCCC. 2003. Estimation, Reporting and Accounting of Harvested Wood Products. United Nations Framework Convention on Climate Change reports FCCC/TP/2003/7 http://unfccc.int/resource/docs/tp/tp0307.pdf, and FCCC/TP/2003/7/Corr.1, http://unfccc.int/resource/docs/tp/tp0307c01.pdf.

USEPA. 2002. Solid waste management and greenhouse gases—A life cycle assessment of emissions and sinks, 2nd Ed. EPA530-R-02-006. United States Environmental Protection Agency. Washington, D.C.

USEPA. 2006a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004. EPA 430-R-06-002. United States Environmental Protection Agency, Washington D.C. http://yosemite.epa.gov/.

USEPA. 2006b. EPA's Combined Heat and Power Partnership. www.epa.gov/chp/what_is_chp.htm.

USEPA. 2007. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005. EPA 430-R-07-002. United States Environmental Protection Agency, Washington DC. http://yosemite.epa.gov/.

Uusivuori, J., E. Lehto, and M. Palo. 2002. Population, income and ecological conditions as determinants of forest area variation in the tropics. Glob. Environ. Change 12:313-323. Elsevier Sci. Ltd.

WBCSD. 2005. The sustainable forest products industry, carbon and climate change. World Business Council for Sustainable Development, Geneva, Switzerland. www.wbcsd.org/web/publications/sfpi-cop11.pdf.