Sequestration of carbon in harvested wood products for the United States

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Abstract

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for countries to report greenhouse gas removals by sinks and emissions from sources. These guidelines allow use of several accounting approaches when reporting the contribution of harvested wood products (HWP) under the United Nations Framework Convention on Climate Change. Using extensions of methods suggested by the IPCC and a software model called WOODCARB II in Microsoft Excel®, this paper presents estimates of the U.S. HWP contribution to annual greenhouse gas removals in the agriculture, forestry, land use, and land use change sector. In 2005, the contribution to removals was 30 Tg (million metric tons) C (carbon) and 31 Tg C for the Production and Atmospheric Flow Approaches, respectively, and 44 Tg C for the Stock Change Approach. This range is 17 to 25 percent of C removals by forests, or would offset 42 percent to 61 percent of residential natural gas C emissions in 2005. The contribution has declined under the Production and Atmospheric Flow Approaches since 1990 and has increased under the Stock Change Approach. The Stock Change estimate has increased because it explicitly includes C in increasing net imports of wood and paper products. The contribution estimates were validated by adjusting the half-life of products in use in order to match independent estimates of carbon in housing in 2001 and annual wood and paper discards to solid-waste disposal sites (SWDS) during 1990 to 2001. Estimates of methane emissions from wood and paper in landfills were also checked against independent estimates of total landfill methane emissions. A Monte-Carlo simulation used to assess the effect of uncertainty in inputs suggests the 90 percent confidence interval for removal contribution estimates under the three approaches is within –23% to +19%.

Harvested wood products (HWP) are any product from wood including lumber, panels, paper, and paperboard, as well as wood used for fuel.[1] There are at least two settings where estimates of additions to carbon stored in HWP or emissions associated with HWP may aid in making decisions about the role of HWP in greenhouse gas emissions from sources and removals by sinks and in managing HWP to influence greenhouse gas emissions and sinks. The first is national level reporting by countries under the UN Framework Convention on Climate Change (UNFCCC). Under the UNFCCC, countries report annually on greenhouse gas emissions and changes in sinks. This information is intended to aid in international discussions and any agreements about managing greenhouse gas emissions and sinks. The second setting is within-country reporting by entities that manage forestland and provide wood for products or reporting by entities that produce wood products. This information is intended to aid national discussions and agreements about managing greenhouse gas emissions and sinks within a country. This paper focuses on providing national level methods and estimates of carbon sinks and emissions associated with HWP.

Annual additions of carbon to stocks of HWP are estimated to be substantial worldwide in comparison to annual net additions to forests (Winjum et al. 1998, UNFCCC 2003), but estimates are uncertain (Skog et al. 2004). This paper presents revised methods and estimates of annual U.S. carbon additions to HWP sinks for annual reports of greenhouse gas emis-

[1] The fate of wood carbon that is harvested but left on harvest sites is accounted for with the forest and with HWP.

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sions and sinks. The results are a revision to earlier estimates by Skog and Nicholson (2000).

Estimates of carbon added to wood products in use and wood products in solid-waste disposal sites (SWDS) have been completely revised for this report using a model that uses more extensive, detailed, and updated data and with the intent of providing better validation and calibration of results as suggested in guidelines published by the Intergovernmental Panel on Climate Change (IPCC 2003, 2006a).

Data and parameters used to make estimates have changed, and estimates are made using three accounting approaches. The basic estimation method has remained the same; that is, estimates are made of the current disposition of wood produced each year beginning 100 or more years in the past. A number of validation/calibration steps have been added, including 1) calibration of model estimates of wood carbon in housing in 2001 to estimates of wood carbon in housing based on the Census of Housing inventory and 2) calibration of estimates of recent annual amounts of wood and paper discarded to landfills with U.S. Environmental Protection Agency (EPA) estimates of discards to landfills.

More extensive, detailed, and updated data have been used to make estimates and provide validation, which come from:

- USDA Forest Service detailed data series on wood and paper production, imports and exports, and on disposition of wood products to end uses;
- An independent estimate of the half-life of single-family homes;
- New or revised data and estimates from the EPA and others on the proportion of wood and paper going to landfills, limits on decay of wood and paper in landfills, and rate of decay in landfills;
- Estimates of wood carbon in the 2001 inventory of residential housing using Forest Service and U.S. Department of Commerce Bureau of Census data;
- EPA and USDA Forest Service estimates of annual amounts of wood and paper being discarded to landfills.

Criteria for estimation

The Intergovernmental Panel on Climate Change (IPPC) has provided Good Practice Guidance to aid countries in making estimates of national greenhouse gas emissions and sinks. Methods in this paper are intended to follow this guidance. The Good Practice Guidance is intended to aid countries

> ". . . in producing inventories that are accurate in the sense of being neither over nor underestimates so far as can be judged, and in which uncertainties are reduced as far as practicable. Good practice guidance further supports the development of inventories that are transparent, documented, consistent over time, complete, comparable, assessed for uncertainties, subject to quality control and assurance, efficient in the use of the resources available to inventory agencies, and in which uncertainties are gradually reduced as better information becomes available." (IPCC 2000 Section 1.3)

In the context of the UNFCCC reporting the terms transparency, consistency, comparability, completeness, and accuracy may be defined as follows (Sevdalina et al. 2003):

Transparency means that the assumptions and methods are clearly explained to allow replication and assessment by users of the information;

Consistency means that estimates are consistent in all their elements with estimates of other years. That is, the same methods are used for the base and all subsequent years, and consistent data sets are used to estimate emissions and sinks;

Completeness means that estimates cover all sources and sinks, as well as all gases, included in the IPCC guidelines as well as other existing relevant source/sink categories that are specific to individual parties and, therefore, may not be included in the IPCC guidelines. Completeness also means full geographic coverage of sources and sinks of a Party;

Comparability means that estimates reported by parties in inventories should be comparable among parties;

Accuracy is a relative measure of the exactness of an estimate. Estimates should be accurate in the sense that they are systematically neither over nor under true emissions or removals, as far as can be judged, and that uncertainties are reduced as far as practicable.

This paper seeks to provide methods, data, and validation sections below that address the criteria that apply to individual country estimates: 1) neither over- nor underestimate, 2) transparent, 3) documented, 4) consistent over time, 5) complete, 6) assessed for uncertainties, 7) able to provide quality control and assurance. We address the criteria to have estimates 8) comparable among countries by providing estimates using each of the main accounting approaches that have been suggested for carbon storage in HWP.

Accounting approaches

The IPCC Guidelines for National Greenhouse Gas Inventories (2006) gives methods that countries can use to estimate and report the annual contribution that carbon changes in harvested wood products make to the aggregate annual carbon removals to sinks and emissions from sources by the agriculture, forestry, and land use (AFOLU) sector in a country. The carbon changes in HWP are considered to be the HWP contribution to annual agriculture, forestry, and land use removals by sinks and emissions from sources. The term HWP contribution is used because it is not correct to say that HWPs remove carbon to sinks (sinks such as forests remove carbon directly from the atmosphere).

The 2006 IPCC guidelines provide methods that allow countries to report HWP contribution under several accounting approaches. In addition, they allow countries to use a default method that assumes no change in carbon stocks in HWPs, but ask that such an assumption be justified. The accounting approaches included in the 2006 IPCC guidelines were developed after input from participants at a series of international meetings.

International workshops identified three approaches to report HWP contribution. These approaches focus on accounting differently for changes in carbon in HWP imports and exports (IPCC 1998, a 2001 Rotorua, New Zealand, meeting,[2] UNFCCC 2003, IPCC 2003 Appendix 3a). The Stock Change Approach focuses on estimating annual carbon stock change in HWP and forests in a country regardless of wood origin. It includes changes associated with HWP imports and excludes

[2] For a summary of the Rotorua, NZ meeting see: www.maf.govt.nz/mafnet/publications/rmupdate/rm7/rmupdate-august01.pdf (accessed 11/12/2007).

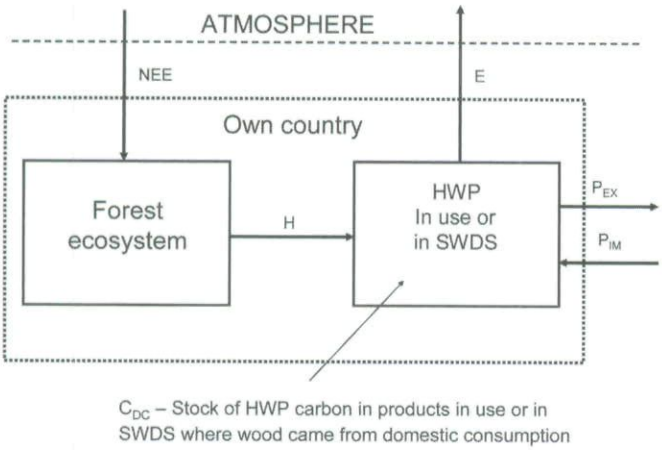

Figure 1. — Carbon flows and stocks for harvested wood products (HWP) for the Stock Change and Atmospheric Flow accounting approaches.

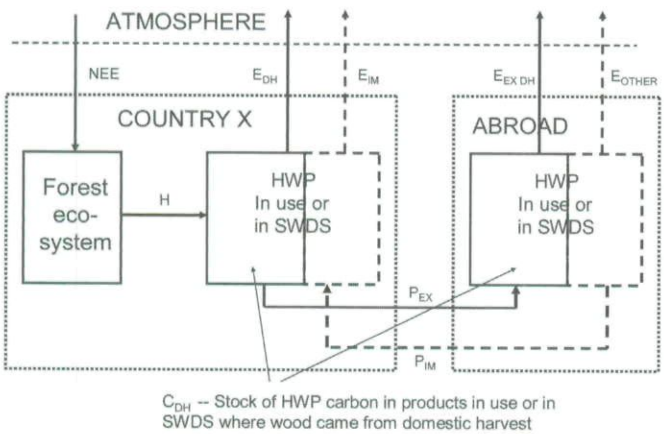

Figure 2. — Carbon flows and stocks associated with forests and harvested wood products (HWP) to illustrate the Production Accounting Approach.

HWP exports. The Production Approach focuses on estimating annual carbon stock change in HWP and forests where the carbon is from trees harvested in the reporting country. It includes tracking of the reporting countries' HWP exports and excludes tracking of imports. The Atmospheric Flow Approach focuses on estimating annual carbon fluxes between the atmosphere and forests/HWPs within a country. That is, emissions from products and removals by forests are accounted for in the country where they occur (**Figs. 1** and **2**).

Attendees at a workshop sponsored by the UNFCCC Secretariat (2003) suggested that methods could be developed to estimate five annual HWP Variables that could then be used to estimate annual HWP carbon change for any of the three approaches. We identify these five variables below using **Table 1** and **Figures 1** and **2**, and then specify methods used to estimate these annual variables. **Table 1**, using variables from **Figures 1** and **2**, provides mathematical expressions that indicate total annual carbon stock change, or carbon flux with the atmosphere, for each of the three accounting approaches, for both forests and HWP.

The portion of each mathematical expression in bold is the contribution of HWP to carbon stock change or carbon flux with the atmosphere. The portion not in bold (NEE –H) is the contribution of the forest to annual carbon stock change, which is identical to net carbon flux with the atmosphere.

Variables 1 through 4 listed below and noted in bold in **Table 1** are needed to estimate annual HWP net carbon stock change or net carbon flux with the atmosphere for any of the approaches. We also estimate harvest (H) in order to calculate annual gross carbon emissions from HWPs for the Atmospheric Flow and Production approaches.

Methods

The following methods indicate how we compute the five annual "HWP Variables" noted above. These methods start with Tier 2 and 3 methods suggested by Pingoud, Skog, Martino, Tonosakli, Zhang, and Ford-Robertson in the IPCC guidelines (2006), add additional products and end-use cat-

Table 1. — Expressions that indicate total annual forest and HWP carbon change for three accounting approaches (see Figures 1 and 2). HWP Contribution as computed in this paper is in bold.

Accounting approach	Annual carbon stock change	Annual net carbon flux with the atmosphere	Gross HWP carbon emissions
Stock change	(NEE – H) + $\mathbf{(\Delta C_{DC})}$		
Atmospheric flow		(NEE – H) + (H – E)	E
		Alternate equivalent expression: (NEE – H) + $\mathbf{(\Delta C_{DC} - P_{IM} + P_{EX})}$	Alternate equivalent expression: H-($\Delta C_{DC} - P_{IM} + P_{EX}$)
Production	(NEE – H) + $\mathbf{(\Delta C_{DH})}$	(NEE – H) + (H – $E_{DH} - E_{EX\ DH}$)	$E_{DH} + E_{EX\ DH}$
			Alternate equivalent expression: (ΔC_{DH} – H)

Variable definitions

NEE is the annual net ecosystem exchange, the annual net carbon that moves from the atmosphere to forests, Mg C yr^{-1}

1. ΔC_{DC} is the annual change in carbon stored in HWP in products in use and products in SWDS where wood came from domestic consumption of products in the United States including imports, Mg C yr^{-1}
2. ΔC_{DH} is the annual change in carbon stored in HWP in products in use and products in SWDS where products used wood from domestic harvest in the United States, Mg C yr^{-1}
3. P_{IM} is the annual imports of wood and paper products including roundwood, chips, residue, pulp, and recovered (recycled) paper, Mg C yr^{-1}.
4. P_{EX} is the annual exports of wood and paper products including roundwood, chips, residue, pulp, and recovered (recycled) paper, Mg C yr^{-1}.
5. H is the annual harvest of wood for products which includes wood removed from harvest sites. This includes fuelwood and the bark associated with the wood removed, Mg C yr^{-1}

E is the annual emission of carbon to the atmosphere in the United States from products consumed in the United States, Mg C yr^{-1}

E_{DH} is the annual emission of carbon to the atmosphere in the United States from products made from wood harvested in the United States (domestic harvest), Mg C yr^{-1}

$E_{EX\ DH}$ is the annual emission of carbon to the atmosphere in other countries from products made from wood harvested in the United States (domestic harvest), Mg C yr^{-1}

egories, develop validation/calibration methods, and were implemented in a model called WOODCARB II using Microsoft Excel®.

We estimate carbon stored in HWP in "products in use" and "products in SWDS (solid-waste disposal sites)" separately. That is, HWP Variables 1 and 2 are divided into two parts corresponding to storage in products in use and products in SWDS.

1A. $\Delta C_{IU\ DC}$ is the annual change in carbon stored in HWP in products in use where wood came from domestic consumption of products in the United States including imports, Mg C yr^{-1}

1B. $\Delta C_{SWDS\ DC}$ is the annual change in carbon stored in HWP in products in SWDS where wood came from domestic consumption of products in the United States including imports, Mg C yr^{-1}

2A. $\Delta C_{IU\ DH}$ is the annual change in carbon stored in HWP in products in use where products came from domestic harvest in the United States, Mg C yr^{-1}

2B. $\Delta C_{SWDS\ DH}$ is the annual change in carbon stored in HWP in products in SWDS where products used wood from domestic harvest in the United States, Mg C yr^{-1}

Note that

$$\Delta C_{DC} = \Delta C_{IU\ DC} + \Delta C_{SWDS\ DC}$$

$$\Delta C_{DH} = \Delta C_{IU\ DH} + \Delta C_{SWDS\ DH}$$

The HWP Variables 1A, 2A, 1B, and 2B are estimates of annual changes in stock of HWP carbon. Estimates of change of carbon held in "products in use" (Variables 1A and 2A) are made by tracking inputs to and outputs from the "products in use" carbon pool. The C inflow to the pool is estimated from historical production or consumption rates of HWPs. Estimates of carbon change in "products in SWDS" (Variables 1B and 2B) are made by tracking inputs to and output from SWDS.

In the case of the "products in use" pool, the outflow from the pool is calculated based on estimated lifetimes and associated discard rates of HWP from use assuming first-order discard rates. First-order means the discard rate is a percentage of the amount in the pool. Data beginning a number of decades in the past up to the present time are used to estimate 1) additions to HWP in use, and 2) discards from use. This procedure is needed to produce an estimate of the existing HWP stock accumulated from historical wood use and current-year discards from those stocks as they go out of use, additions to SWDS, and emissions from burning discards or decay in SWDS. Data inputs to and outputs from HWP stocks are begun in 1900 (1799 in the case of softwood lumber) in order to make valid estimates for recent years.

The HWP Variables 3, 4, and 5 are estimates of annual product imports and exports, as well as annual harvest for products. They are not pools of carbon.

Estimating Variables 1 A and 2 A – Annual change in carbon in "products in use"

Estimates of annual change in carbon in "products in use" for current year t for Variables 1 A and 2 A may be obtained by using Equations [**1**] through [**3**].

For each year T, from 1900 to t, when products were placed in use, estimate the amount remaining in use in year t as:

$$C_{IU\,T\,i\,j}(t) = \exp(-k_{T\,j} \times (t - 1900)) \times \text{Inflow}_{Ti} \times F_{Ti\,j} \quad [\mathbf{1}]$$

$$C_{IU}(t) = \sum_{T=1900}^{t} \sum_{i=1}^{n} \sum_{j=1}^{m} C_{IU\,T\,i\,j}(t) \quad [\mathbf{2}]$$

Estimate the change carbon in products in use as:

$$\Delta C_{IU}(t) = C_{IU}(t) - C_{IU}(t-1) \quad [\mathbf{3}]$$

Where:

$\exp(x)$ is e^x

t is the current year (year for which annual change in HWP carbon stock is being estimated)

Inflow_{Ti} is the annual amount of carbon in primary product i that goes into products in use in year T. Inflows are for years T = 1900 to current year t. Inflow is subdivided into several primary products (i = 1 to n), Mg yr^{-1}. Inflow excludes an estimated loss/ discard as solidwood products are placed in end uses (McKeever 2004),

T is the year when products initially go into the "products in use" pool

i is the primary wood or paper product, i = 1 to n (defined below)

j is the end use for products, j = 1 to m (defined below)

$F_{Ti\,j}$ is the fraction of primary product i inflow in year T that goes into end use j

$k_{T\,j}$ is the annual rate at which the products placed in end use j in year T go out of use. This is the annual rate at which the product is discarded from use. Discarded material may be recycled (including, for example, paper or chipping for mulch), burned, composted, or sent to SWDS. The rate may differ depending on the year products are placed in use, but is constant for the life of products placed in use in a particular year.

Note that

$$k_{Tj} = \ln(2)/HL_{Tj}$$

Where $HL_{T\,j}$ is the half-life in years for products placed in end use j in year T. The half-life is the number of years it takes for half of the initial inflow amount to be discarded.

C(t) is the total carbon held in products in use, Mg.

ΔC(t)is the annual change in carbon in products in use between the end of year t–1 and the end of year t, Mg yr^{-1}

Primary products categories (labeled i) include three for solidwood products (lumber, structural panels and nonstructural panels) and one for all of paper and paperboard products. Lumber includes both hardwood and softwood lumber. Structural panels include softwood plywood and OSB. Nonstructural panels include hardwood plywood, particleboard, MDF, hardboard, and insulation board.

End-use categories (labeled j) include four for solidwood products (single-family housing, multifamily housing, residential upkeep and improvement, and other uses) and one for all paper and paperboard uses. Other solidwood uses includes mobile homes, nonresidential construction, rail ties, rail cars, household furniture, commercial furniture, other manufacturing, shipping, and miscellaneous other.

Equation [**1**] estimates, for current year t, the stock of carbon of primary product i in end use j, where the primary product was originally placed in use in year T. If interest is focused on specific types of products for particular parts of the forest products industry different product categories, end-use categories and half-lives could be developed to give more detailed results.

Equation [**2**] estimates, for current year t, the total stock of carbon held in all primary products held in all end uses that were placed in all end uses from year T = 1900 to the current year t.

Equation [**3**] estimates, for the current year t, the change in total carbon stock in products in use.

Estimating Variable 1A – Annual change in carbon held in products in use in the United States. — Equations [**1**] through [**3**] are used to estimate annual carbon change in solidwood and paper products stored in various end uses in the United States. In this case, the carbon inflow variable to these pools is the annual consumption in the United States of primary wood products. Consumption equals domestic production plus imports minus exports. Annual consumption in carbon units is obtained by converting product units (cubic meters, air dry tons) to tons carbon (C) per year. All references to tons are metric tons. The rate at which solidwood or paper is lost from various end-use pools in a given year is specified by a loss rate (k_{Tj}) and for convenience is also specified by half-life in years, HL_{Tj}.

To make estimates of carbon change in these pools for current year t, the method uses data on Inflow (product consumption = production + imports − exports) back to 1900 from U.S. data sources. The year 1900 was chosen on the assumption that excluding current-year stock changes or emissions prior to 1900 would not violate the Good Practice Guideline to neither over- nor underestimate. Data back to 1800 were used in one case to estimate lumber use in single- and multifamily housing.

Data and parameters used are as follows:

- Production, import, and export data (AF&PA 1999a and b, Hair and Ulrich 1963, Hair 1958, Howard 2003 and 2007, Ince 200, Haynes 1990, Steer 1948, Ulrich 1985 and 1989, UNFAO 2007, USDC Bureau of Census 1976)
- Factors to convert product units to weight of carbon (**Table 2**)
- F_{Tij}, Fractions of primary products used in various end uses (**Table 3**)
- HL_{Tj} is initial estimates of half-lives for products in various end uses (before validation /calibration, **Table 4**)

Estimating Variable 2A – Annual change in carbon held in products made from U.S.-harvested wood (includes exports). — Equations [**1**] through [**3**] are used again to estimate annual carbon change in solidwood and paper products harvested in the United States and stored in various end uses. In this case, the carbon inflow variable to these pools is annual production of all products from wood harvested in the reporting country. This includes roundwood (sawlogs and pulpwood) and recovered paper exported and used in other countries. This does not include any products made in the United States using wood harvested in other countries and imported to the United States.

The annual carbon inflow variables for solidwood and paper products are estimated using Equations [**4**] and [**5**], respectively. The calculations are based on the assumption that solidwood (or paper) products are all alike in the amount of roundwood used to make them in both the United States and in other countries where sawlogs or pulpwood may be exported and used to make products.

Table 2. — Metric tons of carbon per unit of wood or paper product.

	Metric tons carbon per unit[a]	Product unit
Softwood plywood	0.23	cubic meter
OSB/ wafer-board	0.27	cubic meter
Laminated veneer lumber	0.23	cubic meter
Hardwood plywood and veneer	0.28	cubic meter
Softwood lumber[b]	0.22	cubic meter (actual wood content)
Hardwood lumber[b]	0.26	cubic meter (actual wood content)
Particle-board	0.29	cubic meter
Hard-board	0.42	cubic meter
MDF	0.32	cubic meter
Pulp, paper, and board	0.42	metric ton air dry
Other industrial products	0.24	cubic meter
Insulating board	0.16	cubic meter
Pulpwood[b]	0.24	cubic meter
Insulating board	0.45	cubic meter
Hardwood Veneer	0.00085	square meter surface measure
Softwood roundwood[b]	0.22	cubic meter
Hardwood roundwood[b]	0.26	cubic meter

[a]Assumes 0.5 t carbon per od ton wood and 0.43 t C per od ton paper
[b]Roundwood and lumber values are set to match values used in the FORCAB that estimates carbon in U.S. forest inventory and U.S. wood removals for the EPA (2007) reports (Heath 2003).

Table 3. — Fraction of sawnwood, structural panels, and nonstructural panels used in various end uses, selected years 1900 to 1998.[a]

Year	Single-family housing	Multifamily housing	Residential upkeep and improvement	Other
		Sawnwood		
1900	0.30	0.14	0.07	0.49
1948	0.26	0.12	0.10	0.51
1962	0.27	0.14	0.10	0.49
1986	0.30	0.03	0.28	0.40
1998	0.29	0.03	0.22	0.47
		Structural Panels		
1900	0.37	0.11	0.12	0.40
1948	0.37	0.11	0.15	0.38
1962	0.30	0.09	0.17	0.44
1986	0.45	0.04	0.23	0.29
1998	0.47	0.04	0.21	0.28
		Nonstructural Panels		
1900	0.46	0.14	0.12	0.29
1948	0.24	0.08	0.12	0.56
1962	0.22	0.07	0.17	0.55
1986	0.15	0.02	0.24	0.58
1998	0.14	0.02	0.12	0.72

[a]Sources — 1900: Forest Service estimate; 1948: (USDA Forest Serv. 1982); 1962 to 1998: (McKeever 2002)

Table 4. — Initial estimates of half-life parameters for end uses (before validation/calibration).

Parameter	Definition	Value
HL_{H1}	Half-life of solidwood in single-family housing 1920 and before	75 years
HL_{H2}	Half-life of solidwood in single-family housing – 1921 to 1939 (years)[a]	80 years
F_H	Increase in half-life for each 20 year period after 1921 to 1939 (years)	5 years
F_{MF}	Ratio of half-life for solidwood in multifamily housing to half-life in single family housing	0.625
F_{AR}	Ratio of half-life for solidwood in alterations and repair of housing to half-life for single-family housing	0.3215
HL_{OTH}	Half-life for solidwood in all other end uses (years)[b]	30 years
HL_P	Half-life for paper in all end uses (years)[b]	2 years

[a]U.S. housing half-life: Winistorfer et al. 2005; Athena Institute 2004.
[b]Other solidwood and paper half-life: IPCC 2006b.

Table 5. — Factors needed to estimate HWP production from domestic harvest.[a]

Year	Ratio of U.S. sawlog harvest to sawlogs used to make products in the United States	Nonwood fiber use as fraction of total U.S. pulp consumption	Imported woodpulp as a fraction of total woodpulp consumption	Ratio of U.S. pulpwood harvest to pulpwood used to make paper in the United States	Recovered fiber pulp exports	Recovered paper exports	Woodpulp exports
					(Mg carbon)		
	$(S_{LP}-SL_{IM}+SL_{EX})/SL_P$	$F_{non\ wood\ fiber}$	$F_{woodpulp\ imp}$	$(PW_P-PW_{IM}+PW_{EX})/PW_P$	$EX_{rec\ fiber\ pulp}$	$EX_{rec\ paper}$	$EX_{woodpulp}$
1900	1.002	0.185	0.059	1.000	0	13,803	18,502
1920	1.002	0.172	0.193	1.000	0	49,220	31,966
1930	1.003	0.160	0.285	1.000	0	64,947	48,426
1940	1.002	0.096	0.126	1.000	0	102,706	480,938
1950	0.993	0.080	0.139	1.000	0	171,915	95,673
1960	1.004	0.036	0.090	1.000	0	213,727	1,141,534
1970	1.052	0.016	0.080	1.033	0	408,000	3,095,000
1980	1.071	0.010	0.076	1.065	0	2,636,200	3,806,000
1990	1.074	0.004	0.079	1.054	0	6,505,000	5,905,000
2000	1.041	0.004	0.114	1.061	48,081	10,272,000	6,408,568
2001	1.040	0.004	0.124	1.046	16,607	10,597,000	6,166,675
2002	1.037	0.004	0.123	1.033	19,775	1,1267,000	6,253,650
2003	1.034	0.004	0.114	1.027	41,115	13,805,000	5,847,174
2004	1.034	0.003	0.113	1.028	35,380	13,910,000	6,224,901
2005	1.026	0.003	0.112	1.027	36,287	15,906,000	6,412,898

[a]Sources — Hair 1958; Hair and Ulrich 1963 ; Ulrich 1989; Howard 2003; Howard 2007; API 1973; FAO 2007

For solidwood products

$$\text{Inflow}_{T\,i} = P_{T\,i} \times [(SL_p - SL_{IM} + SL_{EX})/SL_p] \quad [4]$$

For paper and paperboard products

$$\text{Inflow}_T = P_T \times (1\text{-}F_{nonwood\ fiber}) \times (1\text{-}F_{woodpulp\ imp}) \times [(PW_p - PW_{IM} + PW_{EX})/PW_p] + EX_{rec\ fiber\ pulp} + EX_{rec\ paper} + EX_{woodpulp} \quad [5]$$

Where:

$P_{T\,i}$ OR P_T is carbon in solidwood (4 products) or paper products (1 product), respectively, produced in the United States in year T. The time subscript, T, is omitted for most right-hand side variables to simplify the equations.

SL_P is sawlogs used to make lumber, plywood, and miscellaneous products in the United States in year T, Mg yr^{-1}

SL_{IM} is sawlogs imported and used to make lumber, plywood, and miscellaneous products in the United States in year T, T, Mg yr^{-1}

SL_{EX} is sawlogs exported from the United States in year T, T, Mg yr^{-1}

$F_{nonwood\ fiber}$ is the fraction of total fiber used to make paper and paperboard that is nonwood fiber in year T.

$F_{woodpulp\ imp}$ is the fraction of woodpulp used to make paper and paperboard imported to the United States in year T.

PW_P is pulpwood used to make paper and paperboard in the United States in year T, Mg yr^{-1}

PW_{IM} is pulpwood imported and used to make paper and paperboard in the United States in year T, Mg yr^{-1}

PW_{EX} is pulpwood exported from the United States in year T, Mg yr^{-1}

$EX_{rec\ fiber\ pulp}$ is carbon in recovered fiber pulp exported in year T, Mg yr^{-1}

$EX_{rec\ paper}$ is carbon in recovered paper exported in year T, Mg yr^{-1}

$EX_{woodpulp}$ is carbon in woodpulp exported in year T. Mg yr^{-1}.

Just as for Variable 1A, estimates of carbon stock change in Variable 2A require data on product production in the United States back to 1900. In addition, special data are needed on domestic roundwood harvest, imports and exports, and paper-related fiber imports and exports in order to compute the ratios needed for Equations [**4**] and [**5**] (**Table 5**). Other parameters including factors to convert original product units to tons of carbon are the same as for Variable 1A. Specifically, the fractions of each product with various end uses ($F_{Ti\,j}$) and the half-life of products in end uses ($HL_{T\,j}$) are assumed to be the same as for Variable 1A. This means that exported products (or logs and chips) are assumed to have end uses in the same proportions as in the United States and that the half-life of end uses is the same as in the United States.

Estimating Variables 1B and 2B – Annual change in carbon held in SWDS in the reporting country and annual change in carbon held in SWDS where wood came from harvest in the reporting country.

Estimates of annual change in carbon in "products in SWDS" for current year t for Variables 1B and 2B may be obtained using Equations [**6**] through [**10**].

Solid-waste disposal sites include dumps, where oxygen is available to decompose all wood and paper over time, and landfills, where a covering is placed over waste periodically and oxygen is sealed out. With limited oxygen, a portion of wood and paper does not decay and will stay permanently in the landfill, and a portion is temporary and will be emitted as CO_2 to or CH_4 over time.

$$\mathbf{C_{SWDS\ PERM}}(t) = \sum_{T=1900}^{t} [D_{SWP}(T) \times (1\text{-}F_{TO\ DUMPS}(T)) \times F_{SWP\ to\ SWDS}(T) \times (1\text{-}DOC_{F\ SWP})\times] + \sum_{T=1900}^{t} [D_{PAPER}(T) \times (1\text{-}F_{TO\ DUMPS}(T)) \times F_{PAPER\ to\ SWDS}(T) \times (1\text{-}DOC_{F\ PAPER})] \quad [6]$$

$$\mathbf{C_{SWDS\ TEMP}}(t) = \sum_{T=1900}^{t} \exp(-k_{SWP\ DUMPS} \times (t\text{-}T)) \times [D_{SWP}(T) \times F_{SWP\ to\ SWDS}(T) \times F_{TO\ DUMPS}(T)] + \sum_{T=1900}^{t} \exp(-k_{SWP\ LF} \times (t-T)) \times [D_{SWP}(T) \times F_{SWP\ to\ SWDS}(T) \times (1\text{-}F_{TO\ DUMPS}(T)) \times DOC_{F\ SWP}] + \sum_{T=1900}^{t} \exp(-k_{PAPER\ DUMPS} \times (t\text{-}T)) \times [D_{PAPER}(T) \times F_{PAPER\ to\ SWDS}(T) \times F_{TO\ DUMPS}(T)] + \sum_{T=1900}^{t} \exp(-k_{PAPER\ LF} \times (t\text{-}T)) \times [D_{PAPER}(T) \times F_{PAPER\ to\ SWDS}(T) \times (1\text{-}F_{TO\ DUMPS}(T)) \times DOC_{F\ PAPER}] \quad [7]$$

$$\mathbf{C_{SWDS}}(t) = C_{SWDS\ PERM}(t) + C_{SWDS\ TEMP}(t) \quad [8]$$

$$\mathbf{\Delta C_{SWDS}}(t) = C_{SWDS}(t) - C_{SWDS}(t-1) \quad [9]$$

$$F_{X\ to\ SWDS} = 1 - F_{X\ BURNED} - F_{X\ REC} - F_{X\ COMPOST}, \text{ Where X is either SWP or PAPER} \quad [10]$$

Where

t is current year (for year for which annual change in HWP carbon stock is being estimated).

T is the year when products are initially discarded and, in part, go into "products in SWDS" pool.

$D_{SWP}(t)$ is the amount of carbon discarded from solidwood products in use in year t, Mg yr^{-1}.

$D_{PAPER}(t)$ is the amount of carbon discarded from paper products in use in year t, Mg yr^{-1}.

$F_{SWP\ to\ SWDS}(T)$ is the fraction of solidwood products discard in year T that are sent to SWDS (includes dumps and landfills).

$F_{PAPER\ to\ SWDS}(T)$ is the fraction of paper products discarded in year T (and not recycled) that are sent to SWDS (includes dumps and landfills).

$F_{TO\ DUMPS}(T)$ is the fraction of solidwood and paper products that are discarded to SWDS that go to dumps rather than landfills in year T.

$F_{X\ BURNED}(T)$ is the fraction of products (X = SWP or paper) discarded in year T that are burned with or without energy production.

$F_{X\ REC}(T)$ is the fraction of products (X = SWP or paper) discarded in year T that are recovered for domestic recycling or for export.

$F_{X\ COMPOST}(T)$ is the fraction of products (X = SWP or paper) discarded in year T that are composted.

$DOC_{F\ SWP}$ is the fraction of solidwood product carbon placed in SWDS that are landfills that is degradable (emitted to the atmosphere).

$DOC_{F\ PAPER}$ is the fraction of paper product carbon placed in SWDS that are landfills that is degradable.

$C_{SWDS\ PERM}(t)$ is the total stock of carbon permanently stored in SWDS in year t.

$k_{X\ Y}$ is the Annual rate at which the products placed in (y =) dumps or landfills are emitted to the atmosphere. Where products are (x =) solidwood products (SWP) or paper. It is equal to ln(2)/ HL, where HL is the half-life in years that HWP carbon is held in dumps or landfills before being emitted to the atmosphere.

$C_{SWDS\ TEMP}(t)$ is the total stock of carbon temporarily stored in SWDS in year t.

$\Delta C_{SWDS}(t)$ is the annual change in carbon in products in SWDS between the end of year t–1 and the end of year t, Mg yr^{-1}.

Equation [**6**] estimates, for current year t, the total stock of solidwood and paper product carbon that is permanently stored in landfill SWDS. Separate estimates are made for solidwood and paper products because of the difference in fractions of discarded products that end up in SWDS and the difference in the fraction of solidwood and paper that is not subject to decay (**Tables 6, 7**). The amounts of solidwood or paper discarded in a particular year t, $D_{SWP}(t)$ or $D_{PAPER}(t)$, are determined by using Equation [**1**] to estimate (for solidwood and paper products separately) how much of the carbon that was placed in use in each year T goes out of use (is discarded) between year t–1 and year t. These estimated changes are calculated for each year products were placed in use, T = 1900 to t, and adding them to together to get a total amount discarded for year t.

Equation [**7**] estimates, for current year t, the stock of solidwood and paper product carbon that is temporarily stored in dumps or landfill SWDS. The rate of decay (or half-life) for

Table 6a. — Percentages indicating disposition of wood after use.[a]

Year	Discarded wood burned	Discarded wood recovered	Discarded wood composted	SWDS Wood or paper going to dumps[b]	Discarded wood to landfills	Discarded wood to dumps
	$F_{SWP\ BURNED}$	$F_{SWP\ REC}$	$F_{SWP\ COMPOST}$	$F_{TO\ DUMPS}$		
	(%)					
1900	29	0	0	100	0	71
1920	29	0	0	100	0	71
1940	30	0	0	96	3	67
1950	30	0	0	90	7	63
1960	31	0	0	84	11	58
1970	21	0	0	67	26	53
1980	9	0	0	25	68	23
1990	16	7	2	2	74	2
2000	15	9	7	2	67	2
2001	15	9	7	2	67	2
2002	14	9	7	2	68	2
2003	14	9	8	2	67	2
2004	14	9	8	2	67	2
2005	14	9	8	2	67	2

[a]Freed (2004) using data from EPA (2006 and prior years), Melosi (1981, 2000) and other sources.
[b]SWDS include both landfills and dumps.

Table 6b. — Percentages indicating disposition of paper after use.

Year	Discarded paper burned	Discarded paper recovered	Discarded paper composted	Discarded paper to landfills	Discarded paper to dumps
	(%)				
	$F_{PAPER\ BURNED}$	$F_{PAPER\ REC}$	$F_{PAPER\ COMPOST}$		
1900	29	0	0	0	71
1920	29	0	0	0	71
1940	30	0	0	3	67
1950	30	0	0	7	63
1960	31	17	0	9	44
1970	21	15	0	21	43
1980	9	21	0	52	17
1990	16	28	2	54	1
2000	15	42	5	37	1
2001	15	46	5	34	1
2002	14	46	5	35	1
2003	14	48	5	32	1
2004	14	49	5	32	1
2005	14	50	5	31	1

the degradable carbon varies by product and type of SWDS (dumps or landfills) (**Table 7**).

Equation [**9**] estimates, for current year t, the change in total carbon stock in products in SWDS.

Estimating Variable 1B – Annual change in carbon held in SWDS in the reporting country. — Variable 1B is estimated using Equations [**6**] through [**9**] where the variables $D_{SWP}(T)$ and $D_{PAPER}(T)$ are amounts of solidwood and paper products, respectively, that are discarded within the United States in year T. These are amounts that are discarded from products previously consumed in the United States.

Estimating Variable 2B – Annual change in carbon held in SWDS where wood came from harvest in the reporting country. — Variable 2B is estimated using Equations [**6**] through [**9**] where the variables $D_{SWP}(T)$ and $D_{PAPER}(T)$ are amounts of solidwood and paper products, respectively, discarded from products made from U.S.-harvested wood. Discarded amounts include discarded products in other countries that were made from U.S.-harvested wood. The wood and paper products exported are assumed to have discard rates and decay rates in SWDS that are within the range of uncertainty for the U.S. rates.

Estimating Variables 3, 4, and 5 – Annual imports and exports of HWP to and from the reporting country and annual HWP harvest. Estimates of annual imports, exports, and harvest for Variables 3, 4, and 5 are needed for the most recent years only. Imports and exports include logs, chips, primary products, woodpulp, and recovered paper. Import and export amounts are only needed for years where we want to estimate HWP contribution under the Atmospheric Flow Approach. This estimate is made by adding annual net exports to the stock change estimate (**Table 1**). Note that these import and export amounts are separate from estimates of imports and exports used to compute Variables 1 A and 2 A. Variable 5, wood harvest plus bark, is needed only for years when a gross emissions estimate is needed for the Atmospheric Flow or Production Approaches. Data sources are indicated in the Reference section.

Validating/calibrating results

Steps are taken as follows to calibrate our estimate of Variable 1A – annual change in carbon stored in products in use in the United States, and Variable 1B – annual change in carbon stored in SWDS in the United States. We validated the results by calibrating the model estimates so they match estimates from two independent sources. Variable 1B estimates were also validated by comparing model estimates of landfill methane emissions from wood and paper to independent estimates of total landfill methane emissions.

Step 1 to validate Variable 1A – Compare and adjust an estimate of total carbon stored in residential housing in 2001 using Equations [**1**] and [**2**] so it matches an independent estimate based on U.S. Census and USDA Forest Service data on number of houses, amount of wood used per house, and amount of wood used for improvements (HHFA 1953, McKeever 2002, USDA FS 1958, 1965; USDC Bureau of Census 2004).

Step 2 to validate Variable 1A – Compare and adjust estimate of wood and paper discarded to SWDS in recent years using Equations [**1**] through [**3**] and discard factors in Equations [**6**]

Table 7. — Wood and paper limits of decay and half-life of decay in landfills and dumps.

Wood products subject to decay in landfills (%)	Paper products subject to decay in landfills (%)	Half-life for degradable portion of wood and paper in landfills[a]	Half-life for wood and paper in dumps[b]
$DOC_{F\ SWP}$	$DOC_{F\ PAPER}$	HL_{SWDS} (years)	HL_{DUMPS} (years)
		Wood	
23	56	29	16.5
		Paper	
		14.5	8.25

[a]Freed and Mintz 2003; IPCC 2006c Vol. 5 Table 3.4.
[b]IPCC 2000, Vol. 5, p 5.7.

and [7] so it matches independent based on EPA estimates of wood and paper discarded to SWDS (U.S. EPA 2002).

These steps directly help calibrate estimates of carbon stock change for the Stock Change Approach and carbon flux for the Atmospheric Flow approach which both use Variables 1A and 1B. These steps may also reduce error in the Production Approach estimate (Variable 2A). This is because a large portion of carbon change in Variable 1 A is also a part of the carbon change in Variable 2A – the part that includes carbon in products that are both produced and consumed in the United States. These validation steps do not help reduce the error in the portion of the Production Approach carbon change that is carbon change in wood and products exported.

The calibration process is explained further in the Results section.

Results

Base-case estimates of the five HWP variables were prepared by adjusting the initial values of the seven half-life parameters in **Table 4** until the two validation/calibration criteria were met: 1) matching WOODCARB II estimates of total carbon in housing in 2001 to census-based estimates and 2) matching WOODCARB II estimates of wood and paper discarded to SWDS to EPA estimates for the period 1990 to 2001.

To meet the calibration criteria, the seven initial half-life parameters were adjusted using the Microsoft Excel® Solver. The Solver adjusted the seven half-life parameters simultaneously until the housing carbon criterion was met exactly and the discard criterion achieved a minimum root mean squared error between the estimates. Resulting Base-case estimates of seven half-life parameters and the five HWP variables are shown in **Tables 8** and **9**, respectively. **Table 9** shows the HWP variables in the format requested for reporting by the IPCC (2006). It is likely that our base-case half-life estimates are not uniquely determined by the calibration process because setting somewhat different initial half-life values (prior to calibration) led to somewhat different calibrated half-life values. The probability distributions for the seven half-life variables were developed as part of the uncertainty analysis discussed below, although these distributions are likely to understate uncertainty because the calibration process does not likely lead to a unique set of half-life values. Base-case estimates of HWP Contribution according to the several accounting approaches are shown in **Table 10** and **Figure 3**.

Table 8. — Estimated solidwood and paper end use half-life parameters after calibration, and their estimated confidence intervals.

Variable[a]	Estimated value	Mean value of distribution	Estimated 90% confidence interval as a percentage difference from the estimated value	
			5%	95%
A	78.0	78.0	−5	5
B	78.0	78.8	−2	7
C	1.97	1.97	−4	4
D	0.61	0.61	−4	6
E	0.30	0.30	−3	5
F	38.0	38.1	−4	5
G	2.53	2.59	−9	20

[a]A. Half-life of solidwood in single-family housing 1920 and before (years).
B. Half-life of solidwood in single-family housing – 1921 to 1939 (years).
C. Increase in half-life for each 20-year period after 1921 to 1939 (years).
D. Ratio of half-life for solidwood in multifamily housing to half-life in single-family housing.
E. Ratio of half-life for solidwood in alterations and repair of housing to half-life for single-family housing.
F. Half-life for solidwood in all other end uses (years).
G. Half-life for paper in all end uses (years).

This results section notes how the HWP Contribution estimate under the Production Approach has changed from previous U.S. estimates, how the HWP Contribution estimates differ among approaches, and how uncertainty was evaluated.

The annual estimates of HWP Contribution under the Production Approach for the period 1990 to 2004 using WOODCARB II are about 52 percent lower than estimates made using the previous version of WOODCARB and previously reported in the EPA "Inventory of Greenhouse Gas Emissions and Sinks" (2006a). For the period 1990 to 2004, the previous estimate under the Production Approach averaged 57 Tg C per year vs. the current WOODCARB II estimate of 30 Tg C per year (**Table 11**).

The lower average WOODCARB II estimate for the Production Approach is due almost entirely to lower estimates for annual additions to SWDS. For the 1990 to 2004 period, old and new annual average additions to products in use are both 14 Tg C. Old and new annual average additions to SWDS are 42 Tg C and 18 Tg C, respectively. Changes that influence estimates of additions to SWDS include 1) revised estimates of the fractions of discarded wood going to landfills and dumps, 2) revised estimates of the fraction of wood and paper not subject to decay in landfills, 3) revised estimates of the rates of decay in landfills and dumps.

Estimates of the fractions of discarded wood going to landfills and dumps were revised using data from EPA (2006 and prior years), Melosi (1981, 2000), and other sources. Estimates of the fraction of wood and paper not subject to decay in landfills were revised, based on Freed and Mintz (2003), using data from studies by Eleazer et al. (1997) and Barlaz (1998). The estimated fraction of C in wood subject to decay in landfills was revised from 3 percent to 23 percent, and the estimated fraction of C in paper subject to decay in landfills increased from 26 percent to 56 percent. The fractions of wood and paper that are not subject to decay, therefore, decreased. Previous estimates of wood and paper subject to decay in landfills were based on Micales and Skog (1997). Estimates of the rates of decay were also updated to 29 and

Table 9. — Annual harvested wood products variables and annual HWP contribution to total AFOLU[a] CO_2 removals and emissions for the United States under the Production Approach, 1990 to 2005.

	Variable number				
	1A	1B	2 A	2B	3
Inventory year	Annual Change in stock of HWP in use from consumption	Annual Change in stock of HWP in SWDS from consumption	Annual Change in stock of HWP in use produced from domestic harvest	Annual Change in stock of HWP in SWDS produced from domestic harvest	Annual Imports of wood, and paper products + wood fuel, pulp, recovered paper, roundwood/ chips
	$\Delta C_{HWP\ IU\ DC}$	$\Delta C_{HWP\ SWDS\ DC}$	$\Delta C_{HWP\ IU\ DH}$	$\Delta C_{HWP\ SWDS\ DH}$	P_{IM}
	Gg C/yr				
1990	17,000	18,500	17,700	18,500	12,700
1991	13,100	18,800	14,900	19,000	11,600
1992	15,700	17,300	16,300	17,700	12,900
1993	17,000	17,900	15,000	18,200	14,500
1994	18,200	17,500	15,900	17,700	15,700
1995	17,300	17,300	15,100	17,500	16,700
1996	17,000	16,600	14,100	16,800	16,700
1997	18,800	17,400	14,700	17,500	18,000
1998	20,300	18,100	13,400	18,000	19,700
1999	22,000	19,000	14,100	18,600	21,300
2000	20,500	18,900	12,800	18,200	22,400
2001	17,300	18,000	8,700	17,100	23,000
2002	18,600	18,700	9,600	17,500	24,600
2003	19,200	17,800	9,700	16,500	26,000
2004	26,300	18,400	12,400	16,600	31,600
2005	25,800	18,600	12,900	16,700	31,800

[a]Agriculture, land use and land use change sector for GHG removals and emissions accounting (IPCC 2006a).

Table 9 (cont'd). — Annual harvested wood products variable and annual HWP contribution to total AFOLU CO_2 removals and emissions for the United States under the Production Approach, 1990 to 2005.

	Variable number				
	4	5	6	7	8
Inventory year	Annual Exports of wood, and paper products + wood fuel, pulp, recovered paper, roundwood/ chips	Annual Domestic Harvest	Annual release of carbon to the atmosphere from HWP consumption (from fuelwood & products in use and products in SWDS)	Annual release of carbon to the atmosphere from HWP (including fuelwoood) where wood came from domestic harvest (from products in use and products in SWDS)	HWP Contribution to AFOLU CO_2 emissions/removals under the Production Approach[b]
	P_{EX}	H	$\uparrow C_{HWP\ DC}$	$\uparrow C_{HWP\ DH}$	
	Gg C/yr				Gg CO_2/yr
1990	15,100	142,300	104,300	106,100	−132,600
1991	15,700	144,400	108,300	110,400	−124,600
1992	16,000	139,400	103,200	105,400	−124,700
1993	14,800	134,600	99,400	101,400	−121,600
1994	15,700	134,800	99,100	101,100	−123,400
1995	17,300	137,000	101,800	104,500	−119,400
1996	16,700	134,500	100,800	103,600	−113,200
1997	16,900	135,400	100,400	103,200	−118,300
1998	15,100	135,000	101,300	103,600	−115,100
1999	15,200	134,900	99,900	102,200	−120,100
2000	16,200	134,500	101,300	103,400	−113,900
2001	15,300	128,600	101,000	102,800	−94,500
2002	15,700	127,600	99,100	100,500	−99,200
2003	16,300	124,900	97,600	98,800	−95,900
2004	17,000	130,500	100,400	101,500	−106,300
2005	18,200	131,800	101,000	102,200	−108,500

[b]Column 8 = −44/12 × (Column 2 A + Column 2B).

Table 10. — Harvested wood products (HWP) Contribution to agriculture, forestry, and land use (AFOLU) emissions/removals by accounting approach (Gg CO_2 /yr).

Inventory year	Stock change[a]	Atmospheric flow[b]	Production[c]
1990	−130,500	−139,300	−132,600
1991	−117,200	−132,300	−124,600
1992	−120,900	−132,600	−124,700
1993	−127,800	−128,800	−121,600
1994	−130,900	−130,900	−123,400
1995	−127,000	−129,000	−119,400
1996	−123,400	−123,500	−113,200
1997	−132,500	−128,400	−118,300
1998	−140,900	−123,800	−115,100
1999	−150,500	−128,400	−120,100
2000	−144,300	−121,400	−113,900
2001	−129,400	−101,400	−94,500
2002	−136,700	−104,300	−99,200
2003	−135,700	−100,300	−95,900
2004	−164,000	−110,200	−106,300
2005	−162,500	−112,800	−108,500

[a]From Table 9: (column 1 A + column 1B) × (-44/12).
[b]From Table 9: ((column 1 A + column 1B) – (column 3 – column 4)) × (-44/12).
[c]From Table 9: (column 2 A + column 2B) × (-44/12).

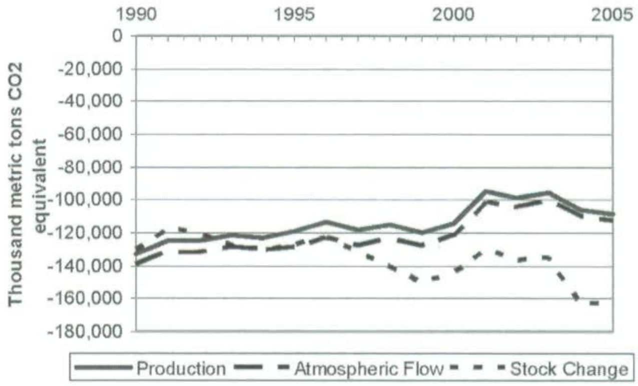

Figure 3. — Harvested wood product contribution to forest sinks and emissions by approach – Gg CO_2/ yr.

14.5 years, for wood and paper in landfills, respectively, and 16.5 and 8.25 years for dumps using values from IPCC (2006c, 2000). These half-lives are the midpoints of the estimated ranges of decay for wood and paper in temperate regions.

Under the Production Approach, the estimate of total accumulation of carbon in products in use in 2004 is now somewhat higher, 1,404 Tg C vs. 1,344 Tg C, and the estimated accumulation in products in SWDS is now lower, 846 Tg C vs. 1369 Tg C.

The estimated HWP Contribution for 2005 under the Production Approach is 30.0 Tg C or −108,500 Gg CO_2 equivalent. The estimated 90 percent confidence interval is –22% and +19%. The estimated total carbon in products and in SWDS in 2005 using the Production Approach is 2,227 Tg with a 90 percent confidence interval of –17% to +18%.

Estimated average annual HWP Contribution over the period 1990 to 2005 is highest for the Stock Change Approach, 37 Tg C/year, followed by the Atmospheric Flow Approach, 33 Tg C/year, and the Production Approach, 31 Tg C/ year. In terms of Gg CO_2, these values are −135,900; –121,700 and –114,500 (**Tables 9, 10, Fig. 3**).

The HWP Contribution under the Production Approach declined between 1990 and 2001 and has since increased (**Fig. 3**). The decline is due primarily to declines in estimated net additions of paper to both products in use and products in SWDS. This is due in part to an estimated decline in production of paper products from domestically harvested trees after 1997. The total stock of carbon in paper products in use is estimated to have declined in several recent years. The annual net additions of solidwood products to products in use and in SWDS has remained relatively constant. The HWP Contribution under this approach could be increased by increasing domestic harvest and/or using a greater proportion of domestic wood and exported wood for long-lived products. If, in reality, wood and paper exported are stored for a shorter time in other countries than the same products in the United States, HWP Contribution under the Production Approach could be larger by retaining harvest in the United States (restrain exports).

The HWP Contribution under the Stock Change Approach increased between 1990 and 2005. This is due primarily to increased net HWP imports. The main increase has been in additions to solidwood products in use. Annual additions to paper products in use and in SWDS have decreased. Additions of solidwood products to SWDS have remained roughly constant. The HWP Contribution under this approach could be increased by 1) increasing harvest and/or increasing the fraction retained in the United States, 2) increasing the amount of HWP imports, or 3) increasing the fraction of wood used in the United States that is stored in long-lived products.

The HWP Contribution under the Atmospheric Flow Approach has followed a path about the same as under the Production Approach—a decline between 1990 and 2001 and an increase since then. The initial decline is due in part to the increase in net HWP imports and their associated emissions. Under this approach, additions to storage from HWP from domestic harvest that remain in the country have been offset by emissions from domestically produced products plus emissions from increasing amounts of imported products. Products retained from domestic harvest have increased (as measured by increasing stocks measured by the Stock Change Approach) but net imports have increased faster. The HWP Contribution under this approach could be increased by 1) increasing the fraction of HWP consumed in the country that are stored in long-lived uses, or 2) decreasing the fraction of HWP consumed that are imported (harvest and produce more in the United States).

By citing above how HWP Contribution could be increased under each approach, we are not suggesting that any particular accounting approach would be best as a means of setting objectives to reduce carbon accumulation in the atmosphere. It is beyond the scope of this paper to evaluate the effects of choosing a particular accounting approach for all countries to use.

The total annual removal of carbon from the atmosphere by U.S. domestic forests AND the HWP from those forests (HWP Contribution under the Production Approach) has averaged 180 Tg C per year between 1990 and 2005 (659 Tg

CO_2 equivalent) (**Table 11**). Harvested wood products contributed about 17 percent to this average. Under the Stock Change Approach, HWP contributed about 20 percent to total C annual stock change in forests and HWP in the United States.

In 2005, under the Production Approach, U.S. forests and HWP offset about 10 percent of gross greenhouse gas emissions – (774 Tg CO_2 equivalent / 7130 Tg CO_2 equivalent) (EPA 2008).

Under the Atmospheric Flow Approach, HWP contributed about 18 percent to the total annual carbon removals from the atmosphere by forests and HWP between 1990 and 2005. However, if we count the global warming potential of estimated methane emissions from wood and paper in landfills, the HWP contribution is lower. Under the Atmospheric Flow Approach average annual HWP Contribution to C removals from the atmosphere (1990 thru 2005) was 33 Tg C (122 Tg CO_2 equivalent). But methane emissions from wood and paper in landfills averaged 2.2 Tg C, or, after adjusting for the radiative forcing of methane, the HWP Contribution is reduced by more than one-half to the equivalent of 15 Tg C[3] (or 56 Tg CO_2 equivalent) (**Table 12**). The net HWP Contribution by placing products in landfills, after accounting for the radiative forcing of methane, is positive for wood additions but negative for paper additions. In 2005, these HWP Contribution estimates were −30 Tg CO_2 equivalents for wood and

[3] To create a factor to convert methane expressed in Tg C to CO_2 equivalent expressed in Tg C we use the following steps: 1) convert Tg C methane to weight of CH_4 (×16/12), 2) convert weight of methane to equivalent weight of CO_2 in radiative forcing terms (×21), 3) convert resulting weight of CO_2 to carbon (×12/44). For 2005, the HWP Contribution under the Atmospheric Flow approach adjusted for radiative forcing of methane is [(31) − (2.0 × (16/44 × 21))] = 16 Tg C.

Table 11. — United States annual net carbon stock change in forests and products and annual net removals from the atmosphere by forests and products - where product carbon comes from domestic harvest (includes carbon in products exported) (Tg carbon, or Tg CO_2 equivalents).

			1990	1998	1999	2000	2001	2002	2003	2004	2005
		Units	Net carbon stock change and net removals from the atmosphere (Production approach)								
1	Forests[a]	Tg C	133	145	133	119	144	163	173	173	173
2	HWP in use	Tg C	18	13	14	13	9	10	10	12	13
3	HWP in SWDS	Tg C	19	18	19	18	17	17	16	17	17
4	Total HWP Contribution (Production)[b]	Tg C	36	31	33	31	26	27	26	29	30
5	Total forests and HWP[c]	Tg C	170	176	165	150	170	190	199	202	203
6	Total forests and HWP[d]	Tg CO_2 equivalent	622	646	607	551	624	697	731	741	744

[a]EPA (2007).
[b]Row 4 = row 2 + row 3.
[c]Row 5 = row 1 + row 4.
[d]Row 6 = row 5 × 44/12.

Table 12. — United States annual net carbon stock change in forests and harvested wood products and annual net removals from the atmosphere by forests and products (Tg carbon, unless noted otherwise).

			1990	1998	1999	2000	2001	2002	2003	2004	2005
		Units	Net carbon stock change (Stock Change Approach)								
1	Forests[a]	Tg C	133	145	133	119	144	163	173	173	173
2	HWP in use	Tg C	17	20	22	20	17	19	19	26	26
3	HWP in SWDS	Tg C	19	18	19	19	18	19	18	18	19
4	Total HWP contribution (Stock change)[b]	Tg C	36	38	41	39	35	37	37	45	44
5	Total forests and HWP[c]	Tg C	169	183	174	158	180	200	210	218	218
6	Total forests and HWP[d]	Tg CO_2 equivalent	620	672	637	581	658	735	771	799	798
7	Net imports of products	Tg C	−2	5	6	6	8	9	10	15	14
8	Methane emissions from HWP in SWDS	Tg C	2.2	2.3	2.2	2.1	2.1	2.1	2.1	2.0	2.0
			Net removals of from the atmosphere (Atmospheric Flow Approach)								
9	Forests[a]	Tg C	133	145	133	119	144	163	173	173	173
10	Total HWP contribution (Atmospheric flow)[e]	Tg C	38	34	35	33	28	28	27	30	31
11	Total forests and HWP[f]	Tg C	171	179	168	152	172	192	201	203	204
12	HWP contribution in greenhouse forcing terms[g]	Tg C	21	16	18	17	12	13	11	15	16
13	Total forests and HWP in greenhouse forcing terms[h]	Tg CO_2 equivalent	566	592	553	498	573	644	676	688	692

[a]EPA (2008).
[b]Row 4 = row 2 + row 3.
[c]Row 5 = row 1 + row 4.
[d]Row 6 = row 5 × 44/12.
[e]Row 10 = row 4 - row 7.
[f]Row 11 = row 9 + row 10.
[g]Row 12 = row 10 – row 8 × ((21 × 16/12 × 12/44).
[h]Row 13 = (row 9 + row 12) × 44/12.

+38 Tg CO_2 equivalent for paper. Therefore, the net emissions associated with HWP in landfills in 2005 including radiative forcing of methane is +8 Tg CO_2 equivalent.

Given the range of values under alternate accounting approaches for HWP Contribution to removals from 15 to 30 to 44 Tg C for 2005, this contribution is equal to 21 percent to 42 percent to 61 percent of the C emissions from residential natural gas use (U.S. EPA 2007).

Validation/calibration

By adjusting the seven half-life parameters in **Table 4** it was possible to calibrate and thereby reduce to some degree the error in the estimate of HWP Variable 1A: Annual change in carbon stored in HWP in products in use where wood came from domestic consumption of products in the United States.

Calibration also decreases error in the estimates of wood and paper discarded to SWDS, which influences the estimate of HWP Variable 1B: Annual change in carbon stored in HWP in products in use where products came from domestic consumption in the United States.

Calibration did not adjust the parameters in **Table 7** that determine the extent and rate of decay of wood and paper in SWDS. That is, we do not currently have a way to fully calibrate HWP Variable 1B: Annual change in carbon stored in HWP in products in SWDS where wood came from domestic consumption of products in the United States

If independent estimates become available of methane emissions from wood and paper in SWDS, then we could adjust parameters in **Table 7** to cause a match to WOODCARB II base-case methane emissions.

The independent estimates of carbon in single and multifamily housing in 2001 are based on U.S. Census and Forest Service survey data (HHFA 1953, McKeever 2002, USDA Forest Serv. 1958, 1965; USDC Bureau of Census 2003) and were estimated in two steps. First, we took the count of houses standing in 2001 by age group and estimated carbon contained in them when they were first built (No. houses × original square meters per house × original wood use per square meter × carbon per unit of wood). Second, we adjusted to estimate of carbon content in 2001 by multiplying by the ratio of average m^2 in the houses in 2001 to the average m^2 in the houses at the time they were built. The result is an estimated 682 Tg carbon in single-family and multifamily houses in 2001.

The WOODCARB II estimate of carbon in housing includes two parts. First, is the part of wood carbon in single-family and multifamily homes (standing in 2001) that was in the homes as originally constructed. Second, is the wood carbon used for residential repair and remodeling that is contained in those homes. These two carbon amounts present in homes in 2001 is influenced by the half-life of each type of home and by the half-life of wood carbon from repair and remodeling. These half-lives were adjusted to have the WOODCARB II estimate match the 682 Tg C estimate using Census data.

Independent estimates of wood and paper discards to SWDS for 1990 to 2001 were obtained from U.S. EPA (2002). WOODCARB II estimates of discards depend on a number of factors including the half lives of wood and paper products in use and the fraction of discarded products that go to SWDS. The half-life estimates of wood and paper products were adjusted in WOODCARB II to minimize the root mean square difference from the EPA estimates. After adjusting the half lives, the EPA and WOODCARB II estimates averaged 17.1 Tg C per year and 14.8 Tg C per year for wood and paper products, respectively.

An additional validation step is to compare WOODCARB II estimates of methane emissions from landfills (**Table 12**) with independent estimates of total methane emissions (U.S. EPA 2007). In 2005, WOODCARB II estimates emissions of methane from wood and paper of 2.0 Tg C (carbon contents of the methane). EPA (2007, Table 8-4) estimates total landfill methane emissions in carbon terms of 4.1 Tg C (= (6.3 − 0.8) Tg CH_4 × (12/16)). This suggests methane from wood and paper is about half of total methane emissions. This is plausible because for 2005 the decomposable fraction of discarded wood and paper products was about 40 percent of the total of wood, paper, food and yard waste—the more readily decomposed portions of municipal solid waste (EPA 2006b).

Evaluation of uncertainty in estimates

An evaluation of uncertainty of the estimates was performed by first identifying 13 sources of uncertainty in input variables; second, assigning a probability distribution to each; and third, conducting a Monte-Carlo simulation to determine the effect on the uncertainty of output variables for 2005, including HWP Variables, the HWP Contribution for each Approach, and HWP carbon stock estimates.

We developed estimated probability distributions for each of the following sources of uncertainty. Individual probability distributions may apply to one or several entire input-time series or to one or several individual input variables. Probability distributions are assumed to be triangular and symmetric except where noted, and 90 percent confidence intervals are given. The distributions specified are assumed to be independent of one another. The evaluation of uncertainty is itself uncertain because the true shape of the distributions is not known for many variables, and data to estimate uncertainty are limited and judgment is required.

Sources 1 and 2. — Solidwood and paper product production and trade time series — The 90 percent confidence interval is ±20 percent and ±15 percent for solidwood and paper products, respectively. Uncertainty level is based on the judgment that national surveys have up to 10 percent error. There is additional error in converting original units to carbon content, and this conversion error is greater for solidwood products than paper products.

Sources 3 and 4. — Factor to convert solidwood and paper products to carbon — The 90 percent confidence interval is ±10 percent for each. Uncertainty is judged to be low because the chemical components of wood and paper are fairly well known.

Source 4. — Carbon in bark as a fraction of wood carbon in logs — The 90 percent confidence interval is ±5 percent for both hardwood and softwood fractions. Uncertainty is based on range in values from Jenkins as cited by Smith et al. (2005). This uncertainty only affects the estimate of total harvest and level of carbon emissions. It does not affect the estimates of HWP Contribution for the various approaches.

Sources 5 and 6. — Fractions of solid wood and paper products not subject to decay in landfills — For these variables, uniform distributions are used to reflect a greater uncertainty in the estimates. For paper, the fraction ranges from 0.329 to 0.552 with and expected value of 0.44. For solidwood products, the fraction ranges from 0.654 to 0.987 with an expected value of 0.77. The expected value and range for paper is based on the decay limits for various types of paper estimated by Barlaz (1998) and Eleazer et al. (1997). The expected value for solidwood is based on estimates made by Barlaz (1998) (Freed and Mintz 2003). The high end of the range (0.987) is based on estimates by Micales and Skog (1997). The low end is a judgment that the uncertainty in the downward direction (–15%) is less than for paper (–25%).

Sources 7 and 8. — Decay rate for solidwood and paper in SWDS (both landfills and dumps)(expressed as a half-life in years)—The 90 percent confidence interval is ±30 percent. The uncertainty in landfill and dump expected values (**Table 7**) are both derived from the range of possible half-life values for landfills for temperate climates identified by the IPCC (2006 Table 3.4).

Source 9. — Export carbon storage as a fraction of storage rate for similar products in the United States — The 90 percent confidence interval for the fraction is 1.1 to 0.5. This fraction is a rough way to account for the uncertainty in both the amount and duration of carbon storage by exported wood and paper in other countries. This uncertainty only affects the uncertainty in the HWP Contribution estimate under the production approach. A judgment is made that storage is more likely to be lower in countries the U.S. exports to (–50%) than it is to be higher (+10%).

Source 10. — Fraction of U.S. solidwood or paper product production that is from imported wood or pulp — The 90 percent confidence interval is ±20 percent. This uncertainty only affects the estimate of HWP Contribution for the Production Approach where carbon storage in imports is excluded. The error is judged to be similar to the error for Sources 1 and 2 because U.S. national surveys are used.

Source 11. — Census-based estimate of carbon in housing in 2001 — The 90 percent confidence interval is ±20 percent. The uncertainty estimate is based on judgment that considered two factors: 1) data on housing and wood use in housing are based on surveys with low error at the national level, and 2) the resulting housing stock estimate was consistent with an independent estimate of the half-life of housing of about 80 years for houses built in the 1920s (Athena Institute 2004,Winistorfer et al. 2005).[4]

Sources 12 and 13. — EPA-based estimates of wood and paper discards to SWDS, 1990 to 2000 — The 90 percent confidence interval is ±20 percent. The uncertainty estimate is based on judgment that such a confidence level results in reasonable range of inferred half-life values of 2 to 3 years for paper products in use.

Probability distributions were not specified for certain other sources of error because it was judged that the error is minimized by the calibration of results to census estimates of carbon in housing and to EPA estimates of discards. These sources include: 1) error in the estimated percentages of each solidwood product going to various end uses over time, 2) error in specification of the shape of the decay functions for products in use (different from first order decay) and 3) different variation in half-life over time for products in use or in SWDS. Calibrated estimates of HWP Variable 1A were also made using linear and inverse sigmoid decay curves to specify how solidwood products go out of use and the recent-year annual changes in HWP Contributions did not differ notably from calibrated estimates made using an exponential decay function.

There is another source of error not specifically evaluated that is likely to be relatively small. This is the error in not explicitly estimating the amount of wood products such as hardwood lumber that are exported and then returned to the United States in finished products such as furniture. The potential amount of such imports for 2005 would be a portion of the 4.5 million tons of carbon exported as solidwood products. If 15 percent of this amount were imported to the United States, that would be less than 1 percent (0.675/ 86.6 = 0.008) of wood and paper placed in uses in 2005. The calibration of WOODCARB II discard rates to EPA solidwood discard rates will tend adjust the estimates of annual change in wood products in use so they reflect imports of previously exported wood, but the estimate of total stock of carbon in wood products in a given year may be underestimated.

The effect of uncertainty on the five HWP Variables and HWP Contribution estimates was evaluated using @Risk™ software, which simulated 380 draws of the random variables and for each draw the seven half-life variables (**Table 4**) were adjusted to calibrate results to the two validation criteria. Draws were made using the Latin hypercube method (Inman et al. 1980), which aids in assuring the entire range of each random variable is sampled. The 380 draws were sufficient to obtain convergence on output distribution means, SDs, and percentile profiles, which were a less than 1.5 percent change for all measures between 360 draws and 370 draws and between 370 draws and 380 draws.

Because the seven half-life variables were adjusted by the calibration process for each draw of the random variables, there is a resulting distribution for each of the seven half-life variables (**Table 8**).

The half-life values after each calibration are influenced by the starting half-life values prior to the calibration. Our starting values are the values after base-case calibration shown in first column in **Table 8**. So, the confidence intervals for the half-lives in **Table 8** are based on the assumption that the starting half-life values are fairly close to correct values for the base case. What this means is that the confidence intervals for the half-life variables in **Tables 4** and **8** may be too narrow (uncertainty is understated). It may be possible to obtain a better evaluation of uncertainty in half-lives if we specified that the starting values of half-lives are random variables. But several alternate half-life value combinations were tested (all meeting the validation criteria), and there was little difference in the estimated five HWP variables for recent years. No attempt was made to improve the estimates of half-life uncertainty by specifying uncertainty in the starting values for half-lives.

Results of the Uncertainty Analysis

Table 13 shows estimated values for the five HWP variables for 2005. The "estimated value" was generated using the "estimated values" of the input variables. The 90 percent confidence intervals for the five HWP variables range from ±10 percent to +25 percent and –24 percent.

Table 13 shows the 90 percent confidence intervals for the HWP Contribution estimates for 2005 under the three approaches. The confidence intervals are about +19 percent to

[4] Housing half-life estimates were also made by Lippke, B. and N. Stevens in an unpublished paper: Housing life cycle: Age of houses in use. University of Washington, Seattle. 3 pp.

Table 13. — Estimated confidence intervals for the HWP variables, HWP Contribution by approach, and HWP carbon stocks for the United States, 2005.

	Variable	Estimated value	90% confidence interval (% difference from the estimated value) 5%	95%
	HWP variable estimates (Tg C per year)			
1 A	Change in carbon in products in use in the United States	25.8	−23	24
1B	Change in carbon in products in SWDS in the United States	18.6	−17	22
2 A	Change in carbon in products in use where wood came from U.S. harvest	12.9	−24	23
2B	Change in carbon in products in SWDS where wood came from U.S. harvest	16.7	−19	25
3	Imports	31.8	−15	15
4	Exports	18.2	−30	7
5	Harvest	131.8	−10	11
6	Emissions from wood held in the United States	101.0	−11	12
7	Emissions from wood harvest in the United States	102.2	−11	12
	HWP Contribution estimates (Gg CO_2 per year)			
	Production approach	−108,500	−22	19
	Stock Change approach	−162,500	−23	19
	Atmospheric flow approach	−112,800	−20	16
	HWP carbon stock estimates - 2005 (Tg C)			
	Stocks in the United States - Total	2,528	−17	18
	In products in use	1,584	−20	20
	In SWDS	943	−14	17
	Stocks from U.S. harvest - Total	2,277	−17	18
	In products in use	1,413	−20	20
	In SWDS	863	−15	16

–23 percent for the Production and Stock Change Approaches and +16 percent to –20 percent for Atmospheric flow. The 90 percent confidence intervals for total HWP carbon stocks in the United States, and carbon stocks from wood harvested in the United States (including exports) are both about ±18 percent.

This evaluation suggests that using the sources and amounts of uncertainty identified, the HWP Contribution estimate under the Production Approach is about as uncertain (+19% to −22%) as the estimate for the Stock Change Approach even though the disposition for exports is highly uncertain. For the decade ending in 2005, wood and paper exports were about 10 percent of total U.S. wood and paper production plus exports (where the exports are products that used roundwood from U.S. forests). Given that the uncertainty is similar for estimates under the two approaches, it appears that additional uncertainty in the disposition of exports (for the Production Approach) is limited and may be matched by uncertainty associated with disposition of imports included under the Stock Change Approach.

Discussion and conclusions

This paper shows it is possible to provide estimates of HWP Contribution to U.S. forest sector removals of carbon from the atmosphere that are supported by calibration and validation against independent estimates of 1) carbon stock in housing, 2) discards of wood and paper in landfills, 3) methane emissions from landfills, and 4) the half-life for housing. Provided the uncertainty evaluation is approximately correct, it is very likely to virtually certain that HWP Contribution has been positive since 1990 under each of the accounting approaches.

Estimated annual HWP Contribution under the Production and Atmospheric Flow Approaches have each declined since 1990 but increased for the Stock Change Approach. For the Production Approach, the decline is due to declining net additions to paper in use and paper in landfills. Net additions to wood in use and landfills have each been steady. For the Stock Change Approach, the net increase since 1990 is due to net increases to both wood in uses and wood in landfills even though there are net declines in additions to paper in uses and paper in landfills. For the Atmospheric Flow Approach, the gross additions to products in use and in landfills are the same as for the Stock Change Approach, but losses are boosted by the amount of net imports and net imports have been increasing.

In 2005, solidwood products contributed about 80 percent of the annual 30 Tg C HWP Contribution under the Production Approach (40% each to products in use and products in landfills). Paper products contributed 4 percent to products in use and 16 percent to products in landfills. The equivalent numbers for the 44 Tg of HWP Contribution under the Stock Change Approach are 58 percent and 32 percent for solidwood in products in use and in landfills, respectively, and 0 percent (zero) and 10 percent for paper products in products in use and landfills, respectively. The relative size of wood and paper contributions is determined to a degree by the somewhat greater inflow of wood carbon into products in use vs. paper (about 18 percent more from 1990 to 2005) but is mostly determined by the longer use life for wood in use relative to paper and the more limited decay of wood in landfills relative to paper. Note that the net contribution of paper in landfills is about zero before accounting for the extra radiative forcing effect of methane emissions.

Because methane emissions from landfills are reported with the waste sector under IPCC guidelines for reporting emissions and sinks, the methane effect is not included in calculating HWP Contribution. But knowing the effect is important in thinking about practices to increase HWP Contribution including the effect of methane. The degree of net methane emissions (after reductions for capture) from wood and paper can determine if HWP Contribution associated with additions to landfills increases or reduces radiative forcing in CO_2 equivalents. Long-term methane emissions from wood or paper are determined by the upper limits on decay and the fraction of methane captured and converted to CO_2 emission. For a wood decay limit of 23 percent, none of the methane needs to be captured to have the wood HWP Contribution from landfills equal about zero in radiative forcing (CO_2 equivalent).[5] For a paper decay limit of 56 percent, 76 percent of methane needs to be captured to have paper HWP Contribution equal zero in radiative forcing. In 2005, methane recovery was about 50 percent. These calculations initially suggest that practices to avoid landfilling of paper would be more effective in reducing radiative forcing than policies to encourage avoidance of sending wood to landfills. But to conclude this, further evaluation is needed to consider the carbon effect of the alternate disposition from the landfill (for instance, recycling or burning), the affect on carbon accumulation in forests, and the effect on use of alternate more carbon intensive products.

The factors identified in estimating HWP Contribution also suggest, in general terms, pathways to increase HWP Contribution (excluding implied goals to increase or decrease imports depending on the accounting approach). These pathways include increasing use of wood for longest lived products, increasing the use life of products (increasing durability and protection), decreasing disposal of products to landfills that decay the most and emit methane. But actions to increase HWP Contribution need to be evaluated as part of a complete life-cycle evaluation including wood-related carbon change in the forest sector, energy sector, and manufacturing sector. We need to look for combinations of changes that increase the sum of carbon offsets by forests, HWP Contribution, wood product substitution for more carbon-emitting alternate products, and wood use for bioenergy/ biofuels. A key question is how to develop policy or market incentives to optimize this combined carbon offset contribution. But to study ways to optimize the sum of carbon offsets, we must clarify our management goals and constraints, and select an accounting approach to use in the evaluation.

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