CARBON CYCLING THROUGH WOOD PRODUCTS: THE ROLE OF WOOD AND PAPER PRODUCTS IN CARBON SEQUESTRATION

KENNETH E. SKOG †
GERALDINE A. NICHOLSON

ABSTRACT

This study provides historical estimates and projections of U.S. carbon sequestered in wood and paper products and compares them to amounts sequestered in U.S. forests. There are large pools of carbon in forests, in wood and paper products in use, and in dumps and landfills. The size of these carbon pools is increasing. Since 1910, an estimated 2.7 Pg (petagrams; $\times 10^9$ metric tons) of carbon have accumulated and currently reside in wood and paper products in use and in dumps and landfills, including net imports. This is notable compared with the current inventory of carbon in forest trees (13.8 Pg) and forest soils (24.7 Pg). On a yearly basis, net sequestration of carbon in U.S. wood and paper products (additions including net imports, minus emissions from decay and burning each year) is projected to increase from 61 Tg/year in 1990 to 74 Tg/year by 2040, while net additions (sequestration) in forests is projected to decrease from 274 to 161 Tg/year. Net sequestration is increasing in products and landfills because of an increase in wood consumption and a decrease in decay in landfills compared with phased-out dumps. If the total projected amount of products required is regarded as fixed, the net carbon sequestration in products and landfills can be increased by 1) shifting product mix to a greater proportion of lignin-containing products, which decay less in landfills; 2) increasing product recycling; 3) increasing product use-life; and 4) increasing landfill CH_4 burning in place of fossil fuels.

Research into reducing global carbon emissions and increasing carbon sequestration has been spurred by recognition that increasing levels of CO_2 in the atmosphere will affect the global climate. The main nonhuman sources of atmospheric CO_2 are animal respiration and decay of biomass (16). However, increases in atmospheric levels are attributed mainly to fossil fuel burning and deforestation. While efforts to hold down emissions of CO_2 continue, increases in CO_2 emissions can also be offset, to a degree, by accumulation in carbon sinks such as plant biomass and oceans. It is therefore prudent to focus research efforts both on increasing carbon in sinks and reducing carbon emissions. To this end, at the United Nations Conference on Environment and Development in 1992, the United States joined other nations in signing the Framework Convention on Climate Change, an international agreement to address the problems of global climate change. To implement the agreement, the President developed the Climate Change Action Plan (3), which set the objective of returning U.S. greenhouse gas emissions to 1990 levels by the year 2000. The plan set a goal to hold down growth of U.S. carbon emissions by 100 Tg[1] between 1990 and 2000 (3). The 1997 Kyoto Conference of the Parties to the United Nations Framework Convention would, if ratified by the U.S. Senate, commit the U.S. to reducing carbon emissions to 7 percent less than the 1990 level (14). In 1992, U.S. wood consumption was 19×10^9 ft.[3] or 147 Tg carbon (5).

In 1990, U.S. CO_2 emissions were 1,367 Tg carbon equivalent (3). Wood and paper products play an important role in mitigating these emissions by sequestering carbon, which helps to mitigate carbon buildup in the atmosphere. There are currently large pools of carbon

The authors are, respectively, Project Leader, Timber Demand and Technology Assessment Research, USDA Forest Serv., Forest Prod. Lab., One Gifford Pinchot Dr., Madison, WI 53705; and Administrator of Economic Studies, Power Plant Research Program, Maryland Dept. of Natural Resources, 580 Taylor Ave., Annapolis, MD 21401. The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Dept. of Agriculture of any product or service. The research for this paper was supported, in part, by a grant from the Environmental Protection Agency, Office of Policy, Planning, and Analysis. We thank Rich Birdsey, Linda Heath, and two *FPJ* reviewers for helpful comments on earlier drafts of this paper. This paper was received for publication in June 1997. Reprint No. 8675.
† Forest Products Society Member.
© Forest Products Society 1998.
Forest Prod. J. 48(7/8):75-83.

[1] Carbon is commonly measured in teragrams (Tg), which is $\times 10^6$ metric tons, or petagrams (Pg), which is $\times 10^9$ metric tons. There is 1 Tg of carbon in $\sim 130 \times 10^6$ ft.^{3} of wood or 2.2×10^9 board feet of soft-wood lumber.

in forests, in wood and paper products in use, and in dumps and landfills. The size of these carbon pools is increasing. The analysis presented in this study estimates that, currently, additions to wood and paper in products in use and in landfills sequester ~61 Tg/year after deducting for CO_2 and CH_4 emissions from burning or decay. These sequestration contributions are substantial compared with the additional sequestration in U.S. forests each year. We use the term sequestration to refer to the net additions, for a period of time, to a stock or pool of carbon: carbon in forests, carbon in forest products in use (including net imports), or carbon in forest products in landfills. This expands the use of the term beyond its common use referring to net additions of carbon to forests. We also use the term additions to imply net additions in this study. In recent years, net addition or sequestration of carbon in U.S. forests has averaged 250 Tg/year, including trees, understory plants, forest floor, and soils on all U.S. forest land (6). By 2040, the annual sequestration in forests is projected to decline to ~160 Tg/year (6) while our analysis estimates sequestration of carbon in wood and paper products in use and in landfills is projected to increase to -74 Tg/year. Wood and paper products contribute to CO_2 and CH_4 emissions to the atmosphere when they are burned or decay in landfills. In 1990, ~74 Tg of carbon were emitted, largely as CO_2, by burning products for energy. About 10 Tg were emitted as CO_2 and CH_4 by decay and burning without energy recovery.

Carbon sequestration in wood and paper products has been assessed in several other studies. Some studies assess carbon sequestration for a range of hypothetical conditions of forest growth, harvest, end use, and disposal (13). Other studies, similar to this one, estimate the actual stocks and flows of carbon from U.S. forests to products in use, to dumps or landfills, to burning and emissions from decay including reconstruction of historical flows and projections (7,12). This study presents similar results with three improvements: 1) use of greater detail in the changing composition of end uses of wood and paper products; 2) inclusion of net imports of wood and paper products in carbon sequestration estimates; and 3) use of new, much lower decay estimates for wood and paper in landfills including separate estimates of CO_2 and CH_4 portions. These improvements help provide a clearer understanding of how sequestration in products may change. We compare our results in detail to those of Heath et al. (7).

The purpose of this study is to show an in-depth method of providing historical estimates and projections of U.S. carbon sequestration in wood and paper products and compare those estimates to amounts sequestered in U.S. forests. We also use this method to explain how several factors have changed, and will continue to change, the pattern and amounts of carbon sequestered. These factors include the relative shift from production of solid wood products to paper products and the shift from disposal in dumps to use of landfills and more recycling. We compare our results to another study that made similar estimates (7).

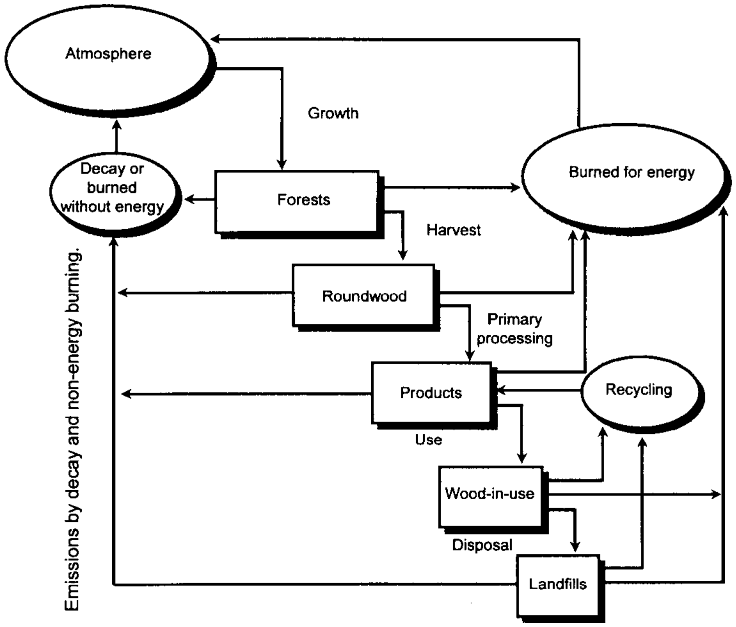

Figure 1.–Cycling of carbon through wood and paper products.

This analysis is unlike analyses that specify certain limited or hypothetical forest areas that have a certain pattern of growth, removals, product use, product disposal, and decay (13). Such analyses arc valuable in evaluating the dynamics of limited areas but are not designed to cover actual events encompassing all U.S. forests.

For our historical estimates (post 1910) and projections, we track carbon added to, and emitted from, stocks of wood and paper products in the United States. Additions to U.S. carbon sinks come from wood in trees harvested in the United States and from net imports (imports minus exports) of logs and wood and paper products. Historical harvest and product use data are needed to estimate future emissions from products that were manufactured in the past. Carbon contained in harvested timber and net imports is tracked through primary processing into products and end uses **(Fig. 1)** (adapted from Row and Phelps (12)). Wood or paper residues are generated at all phases of processing and are either reused in a product, burned with or without energy, or dumped (historically) or landfilled (currently). Wood and paper products are tracked to various end uses where they have a limited life span and are retired from use and sent to landfills or burned. The fate of logging residues is not considered in this model, since decay and emissions from these residues are modeled as part of the forest ecosystem (6).

METHODS

Historical data and long-range projections are used to track roundwood and carbon disposition through to end uses. To track carbon beyond end uses to waste products, burning, disposal, and decay, estimates are made for waste generated in use of primary products and for rates of product disposal, decay, and burning.

Historical data on wood harvest and end use from 1909 through 1986 are from U.S. Department of Agriculture, Forest Service surveys and estimates (17-24,26). Historical wood harvest, through

1986, was tracked from primary products to end uses to dumps or landfills (10). Projections were made of wood harvest and primary product production using the models that were used for the U.S. Department of Agriculture, Forest Service 1993 Resource Planning Act (RPA) Assessment Update (5,8). These projections were made by the North American Pulp and Paper (NAPAP) model and Timber Assessment Market (TAMM)/ ATLAS forest sector models. Historical information and projections from NAPAP and TAMM/ATLAS were processed by the WOODCARB mode1 to estimate the following, through 2040: 1) net carbon sequestered in products in use each year; 2) net carbon sequestered in landfills or dumps each year; 3) carbon released by burning where usable energy was produced each year; and 4) carbon released by decay or burning without energy produced each year.

The NAPAP model simulates operation of markets and projects consumption of pulpwood, use and change of processing technology, and consumption of pulp and paper. It projects consumption of hardwood and softwood pulpwood, 4 categories of recycled paper, and production and trade of 13 categories of pulp and paper. The TAMM model and the ATLAS timber inventory projection model simulate the operation of solid wood markets and project consumption of timber, production of lumber and panel products, and end use of lumber and panels in construction, manufacturing, shipping, and other applications. The TAMM model also tracks imports and exports of logs, lumber, and panels. The ATLAS model uses NAPAP and TAMM calculations of timber removals to project U.S. forest inventory. The WOODCARB model is an addition to the TAMM model that tracks carbon in all timber removed from U.S. land plus carbon in net imports of logs and wood and paper products.

The following sections explain the methods used to track the flow of carbon in wood from forests, through products and end uses, to landfills and emission by decay or burning.

CARBON TRANSFER

From forests to harvested roundwood. –The carbon in wood harvested each year was estimated through 2040, beginning with wood harvested in 1909 and following each year's wood harvest through to its final disposition. Carbon in wood residue left on harvest sites is not included. Cubic feet of roundwood removed in each of nine U.S. regions is converted to weight of carbon using factors shown in **Table 1** (1). Carbon in logs imported is added to the roundwood sources, and carbon in logs exported is deducted. The distribution of uses of imported logs is assumed to be the same as the distribution of uses for domestic sawlogs.

From roundwood to primary products and residue. –Annual historical estimates and projections of detailed product production from the NAPAP and TAMM models were used to divide roundwood consumed into primary product, wood mill residue, and pulp mill residue categories **(Table 2).** In most areas, solid wood residues are used almost entirely as raw materials for other processes or arc burned for energy. Only a small portion of residues is left to decay or is burned without energy (11). Carbon in imports of primary solid wood and paper products is added to each product category, and carbon in exports is deducted.

From primary to end-use products and disposal. – Carbon in solid wood prod-

TABLE 1. — Carbon per unit of roundwood by region.

Region	Carbon per unit roundwood	
	Softwood factors	Hardwood factors
	(kg/m^3 (pcf))	
Pacific Northwest-west	242.0 (15.11)	188.4 (11.76)
Pacific Northwest-east	212.9 (13.29)	188.4 (11.76)
Pacific Southwest	242.0 (15.11)	188.4 (11.76)
Northern Rocky Mountains	215.0 (13.42)	191.7 (11.97)
Southern Rocky Mountains	212.9 (13.29)	188.4 (11.76)
North Central	201.0 (12.55)	277.6 (17.33)
North East	194.6 (12.15)	307.7 (19.21)
South Central	270.7 (16.90)	317.5 (19.82)
South East	270.7 (16.90)	317.5 (19.82)

TABLE 2. — Categories of roundwood consumption.

Historical estimates	Projections[a]
Solid wood products and wood mill residue	
Lumber	HW and SW lumber
Structural paneling	HW and SW plywood
Nonstructural paneling	HW and SW in reconstituted panels
Railway ties	HW and SW miscellaneous products
Miscellaneous products	HW and SW for roundwood for fuelwood
Roundwood for fuelwood	HW and SW wood mill residue
Wood and bark mill residue	HW and SW bark mill residue
Paper and paperboard products and pulp mill residue	
Paper with long use-life	Newsprint
Paper with short use-life	Coated free sheet
Paperboard	Uncoated free sheet
Sludge and pulp liquor	Coated groundwood
	Tissue and sanitary
	Specialty
	Kraft packaging
	Linerboard
	Corrugating medium
	Solid bleached board
	Recycled board
	Construction paper and board
	Dissolving pulp
	Wood and bark waste
	Sludge and pulp liquor

[a] HW = hardwoods; SW = softwoods.

TABLE 3. — End-use categories used to estimate time carbon remains sequestered.

Solid wood products	Paper and paperboard
Multifamily housing	Use and disposal categories
Mobile homes	Newsprint
Residential upkeep and repair	Boxes
Nonresidential construction	Office paper
Manufacturing	Coated paper
Shipping	Recycled paper categories
Furniture	Old newspaper
Railroad ties	Old corrugated containers
Miscellaneous uses	Mixed paper
Construction waste	Pulp substitutes and high grade deinking
Demolition waste	

TABLE 4. — Duration of carbon sequestration in end uses of wood and paper.

End use	Half-life of carbon
	(yr.)
Single-family homes (pre-1980)	80
Single-family homes (post-1980)	100
Multifamily homes	70
Mobile homes	20
Nonresidential construction	67
Pallets	6
Manufacturing	12
Furniture	30
Railroad ties	30
Paper (free sheet)	6
Paper (all other)	1

TABLE 5. — Estimated maximum proportions of wood and paper that are converted to CO_2 or CH_4 in landfills.

Product type	Maximum carbon converted
	(%)
Solid wood	3
Newsprint	16
Coated paper	18
Boxboard	32
Office paper	38

ucts is estimated for a number of end-use categories **(Table 3)** to estimate the time carbon remains sequestered in those products. The TAMM projections are used to divide products into these categories. Paper and paperboard products are not tracked to their final end uses, but the time in use is estimated directly for the various primary products listed in **Table 3.** When products are placed in end uses, such as house construction for solid wood and magazine production for paper, some wood or paper is discarded. We assume 8 percent loss for solid wood products and 5 percent for paper and paperboard products as they are placed into end uses such as construction or publications. Lost or discarded wood or paper is tracked to recycling, disposal in landfills or dumps, or emission by burning. We estimate ~24 percent of paper and paperboard waste (after recycling) was burned in 1993; this percentage increases to 26 percent for the year 2000 and thereafter (25).

We adapted an equation used by Row and Phelps to estimate the fraction of carbon remaining in end use for each year after the product was placed in use (12, p. 37). The key parameter in the equation is the half-life for carbon in each end use **(Table** 4). The half-life is the time after which half the carbon placed in use is no longer in use. Disposition of carbon after use includes recycling, disposal in landfill or dump, or emission to the atmosphere by burning (with or without energy produced).

The rate of retirement of wood from end uses is constant for a period, then accelerates for a while near the median life, and finally slows down after the median life. Some wood or paper items are expected to have very long lives in uses such as historical buildings, books in libraries, and antiques. The rate of retirement of paper products from use is very fast; the half-life is 1 year or less, except for paper in long-lived publications (free sheet paper), which has a half-life of 6 years.

CARBON DISPOSAL IN DUMPS AND LANDFILLS

The length of time wood, as opposed to paper, remains in end uses may have only a minor effect on the net amount of carbon sequestered in products in the long run. If, when taken out of use, products are disposed of in a modem landfill, the literature indicates that they will stay there indefinitely with almost no decay (9). What may be more important for carbon sequestration or emissions is how much wastewood from discarded wood products or demolition is burned (emitting carbon with or without energy) or how much is recycled (reducing harvest from forests).

Wood and paper sent to landfills (or dumps prior to 1986) includes residue from solid wood mills (in very limited amounts), construction and demolition waste, and discarded paper, paperboard, and solid wood products. These same materials are sometimes burned with or without energy. Prior to 1972, most materials were placed in dumps, where a proportion was burned and contents were more exposed to oxygen and decayed more completely. Legislation then required that dumps be phased out by 1986. Since then, materials have been placed in landfills. Materials in landfills are periodically sealed, which prevents oxygen from entering. For dumps, we estimate that 6.5 percent of waste was burned. We assume the remaining waste decayed evenly during a 96-year period, with a greater proportion of carbon being released as CO_2 than as CH_4 because of a greater mix of oxygen with the materials.

The pattern of landfill decay is markedly different for wood than for paper. A relatively short time after material is placed in a landfill, the material is covered and oxygen is prevented from entering the landfill. While oxygen is available, white-rot fungus can decay lignin to a limited extent. However, the oxygen is consumed rapidly. After the oxygen is gone, only anaerobic bacteria remain. These organisms cannot break down lignin, but they can break down exposed cellulose and hemicellulose. However, anaerobic bacteria cannot reach cellulose or hemicellulose that is enclosed in lignin (4,27). This means that very little decay of solid wood occurs. Newsprint, which has a lignin content of 20 to 27 percent, is also very resistant to decay. Other papers with less lignin are somewhat more subject to decay. In general, much less than half of the carbon in wood or paper is ever converted to CO_2 or CH_4 **(Table 5)** (9).

Not only is the decay of wood and paper highly limited in landfills, but the proportion of carbon emitted as CO_2 is limited to ~40 percent, versus ~60 percent as CH_4, due to the limitation of oxygen and the greater production of CH_4

by anaerobic bacteria. Half of the total CO_2 is emitted in ~3 years, while half the total CH_4 is emitted in ~20 years (9).

The shift to greater CH_4 production in landfills compared with that in dumps is important because CH_4 is 25 times more effective than CO_2 as a heat-trapping greenhouse gas. In our tracking of CH_4 production, we assume 10 percent of the CH_4 is converted to CO_2 by microorganisms as it moves out of the landfill. We assume that the proportion of landfill CH_4 that is burned will increase from the current 15 percent level to 58 percent by 2040.

CALCULATING NET DRAIN OF CARBON FROM THE ATMOSPHERE TO THE UNITED STATES

One objective of this study is to estimate the combined effect of the forestry sector on net drain of carbon from the atmosphere through the year 2040. This includes sequestration in forests, products, and landfills, and emissions by burning and decay, including emissions from imported products. This section will show why net annual gain in carbon in U.S. stocks (forests, products, landfills) is greater than the net drain to the United States from the atmosphere by the amount of net imports.

Gross additions of carbon to forest trees and soil per year (G) may be expressed as the change in carbon inventory in forests during a year plus carbon in material harvested for products:

$$G = CIC + HP \qquad [1]$$

CIC is net additions to the inventory of carbon in the forest per year (carbon inventory change). It accounts for any emissions from decay of dead trees or organic material in the soil. It also accounts for emissions from decay or burning of logging residue left after harvesting. *HP* is harvest and removal of wood carbon for products and wood burning per year. We only include burning of wood after it has been harvested and removed from the forest. We do not include emissions from forest fires in this analysis. Harvesting for products could reduce emissions from fire and increase sequestration in products. This important effect should be the subject of further research.

We now focus on the pool of carbon in the atmosphere and estimate how the forest sector drains or adds to this pool. We include the emissions from imports in our variables for emissions from the United States. The rate of drain from the atmosphere per year may be expressed as follows (positive terms represent drain from the atmosphere, negative terms represent additions to the atmosphere):

$$S = G - WB - ECO_2 - ECH_4 \qquad [2]$$

S is net sequestration of carbon per year (or net drain of carbon from the atmosphere). G is gross addition of carbon in forest trees and soil per year, including all growth, even that which is later harvested during the year for products and fuel. *WB* is emissions of carbon as CO_2 from burning wood, paper, or CO_2 from burning CH_4 for energy production. ECO_2 is emissions of carbon as CO_2 from decay or burning without energy. ECH_4 is emissions of carbon as CH_4 from decay in landfills, not including CH_4 emitted from wood products in other places such as sewage systems.

The following steps convert Equation **[2],** which expresses annual net carbon drain from the atmosphere to the United States in terms of forest sequestration and emissions, into an equation that expresses the same drain using variables for the annual change in stock of carbon in products in use (P) and stock of product carbon in landfills (L).

Let:

$$WB = WBWOOD + WBCH_4$$

WBWOOD is carbon released from burning wood and paper and $WBCH_4$ is carbon released from burning CH_4 released from landfills.

We may express the net additions to the pool of products in use (P) as the amount harvested minus the drains from products in use plus net imports.

$$P = HP - SL - WBWOOD + (I - E) \qquad [3]$$

SL is the amount of carbon shifted to landfills from the pool of products in use each year.

The net addition of carbon to landfills each year is the amount shifted from products in use (*SL*) minus releases:

$$L = SL - (WBCH_4 + ECO_2 + ECH_4) \qquad [4]$$

By solving Equation **[4]** for *SL*, substituting in Equation **[3],** and solving for *HP, we* have:

$$HP = P + L + WB + ECO_2 + ECH_4 + (I - E) \qquad [5]$$

By substituting Equations **[1]** and **[5]** in Equation **[2],** we obtain an expression for total net sequestration per year that includes the effect of forest growth (*CIC*), net additions to products in use and landfills (P and L), and emissions from burning and landfill decay (*WB*, ECO_2, and ECH_4):

$$S = (CIC + P - (I - E) + L + WB + ECO_2 + ECH_4) - WB - ECO_2 - ECH_4 \qquad [6]$$

If we focus on the amounts of carbon flows (rather than the different effects of CO_2 and CH_4 in the atmosphere), we may simplify the calculation of carbon drain from the atmosphere.

$$S = CIC + P + L + (I - E) \qquad [7]$$

Equation **[7]** indicates that net drain from the atmosphere is the sum of net additions to carbon in forests, net addition to products in use, and net additions to landfills minus net imports.

Annual change in carbon in stocks in the United States may be expressed as:

$$\text{Change in stocks} = CIC + P + L \qquad [8]$$

To interpret the difference between Equations **[7]** and **[8],** recall from Equation **[3]** that products in use (P) is harvest (*HP*) increased by net imports minus emissions and shifts to landfills. So the annual change in stocks includes net imports while annual drain from the atmosphere does not.

Equation **[7]** does not include carbon emissions from fossil fuels burned for energy in forest sector activities. The sequestration calculated here is the dividend obtained by the forestry activities of the sector. If one were to compare carbon sequestration effects between a forest and a nonforest industry that both provided, say, housing components, one would need to account for not only the fossil fuel emissions of these industries but also any carbon sequestration. The net sequestration effect of using wood housing components is bolstered by the forest regrowth and product or landfill sequestration effects calculated here.

Some may ask why wood burning does not seem to add to sequestration since it replaces fossil fuels and trees grow to absorb the carbon emitted by wood burning. The answer lies in the fact that Equation **[7]** only indicates the net addition to sequestration in 1 year and does not account for how the value for carbon inventory change (*CIC*) may be higher in a future year or years as a result of harvesting and burning wood in the current year. A forest growth and yield model is needed to evaluate the degree to

TABLE 6. — Estimates of carbon sequestered, emitted, and consumed in U.S. annually (Historical reconstruction 1910 to 1980, with projections to 2040 (RPA Base Case)).

	Carbon				
Year	Added to products in use	Added to landfills	Emitted by burning with energy	Emitted by decay or burning without energy	Total consumed each year
	(Tg)				
Historical reconstruction					
1910	24.3	1.1	88.4	10.6	124.4
1920	22.9	3.1	51.9	14.7	92.6
1930	12.8	4.1	44.6	15.5	77.0
1940	14.0	5.3	35.0	20.4	74.7
1950	13.6	6.3	37.4	25.5	82.8
1960	9.0	7.1	34.6	30.6	81.3
1970	12.4	9.2	32.8	35.9	90.3
1980	11.8	27.9	48.1	19.2	107.0
Base Case projections					
1990	26.0	33.4	74.4	11.4	145.2
2000	25.0	32.5	88.1	14.3	159.9
2010	24.6	38.0	96.8	15.3	174.7
2020	25.6	42.6	103.0	16.4	187.6
2030	24.4	47.0	109.5	17.1	197.9
2040	22.9	50.8	119.0	17.5	210.2

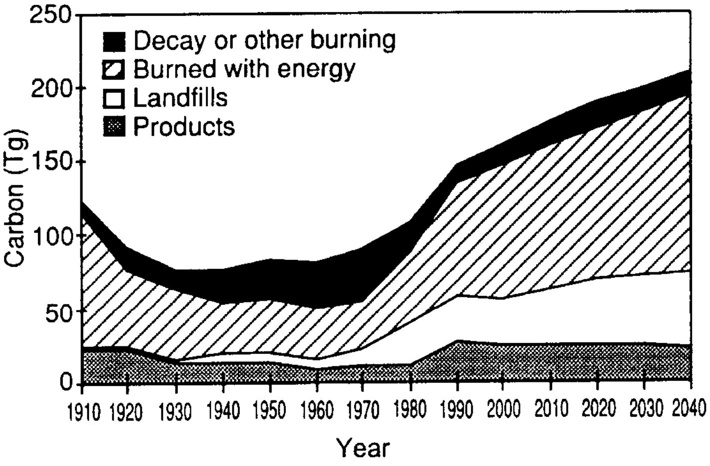

Figure 2. – Base Case scenario – Annual net carbon additions to products and landfills, and annual emissions from burning with energy and decay and other burning.

which the *CIC* value is higher in the future due to harvest and use of wood for energy in the current year. In the analysis for this study, we used the ATLAS inventory growth and yield model to calculate actual future increases in forest growth.

Calculating the greenhouse gas effect of net carbon drain to the United States

The greenhouse gas effect of net carbon drain by the forest sector is determined in part by whether carbon is emitted to the atmosphere as CO_2 or as CH_4. A CH_4 molecule is 25 times more effective in trapping heat than a CO_2 molecule (16). However, CH_4 lasts an average of 10 years in the atmosphere, while CO_2 lasts at least 50 years before breaking down. The long-term greenhouse effect of a CH_4 molecule has been estimated to be ~21 times greater than the effect of a CO_2 molecule. To approximate the greenhouse gas effect of net carbon drain (*S*), we need to convert carbon emitted as CH_4 (ECH_4) to its weight in terms of the heat trapping effect of carbon in CO_2. That is, an atom of carbon in CH_4 results in 21 times more heat trapped than an atom of carbon in CO_2.

$$S_g = (CIC + P - (I - E) + L + WB + ECO_2 + ECH_4) - WB - ECO_2 - 21(ECH_4) \qquad [9]$$

$$S_g = CIC + P\,(I - E) + L\,(20(ECH_4) \qquad [10]$$

S_g is net carbon drain after converting the CH_4 emissions term to CO_2 equivalent weight.

About 40 percent of the carbon from wood and paper decaying in landfills is emitted as CO_2 and about 60 percent as CH_4. The CO_2 is released quickly, while oxygen is present, and the CH_4 is released very slowly after oxygen is depleted (9). Since half the carbon is emitted as CH_4, converting it to CO_2 could have a notable effect in raising the carbon drain by the forestry sector.

Results

Several key factors determine the pattern of historical and projected carbon sequestration and emissions from wood and paper products.

The carbon contained in annual domestic roundwood harvest plus net product imports declined between 1910 and the mid-1960s (from 124 to 74 Tg/year) in part as a result of steadily decreasing fuelwood use (10,17-24). However, the amount of carbon in roundwood doubled from the mid-1960s (74 Tg/year) to 1995 (150 Tg/year) and is projected to increase to 210 Tg/year by 2040 in our Base Case projections **(Table 6; Fig. 2).**

The distribution of roundwood into primary products has shifted from a mix of primarily solid wood products and fuelwood to a mix that includes an increasing proportion of paper products and more burning of residue and black liquor. Carbon in solid wood products is projected to double between 1950 and 2040 (30 to 60 Tg), while pulpwood used in paper production will increase 600 percent (to 81 Tg) by 2040. Pulpwood use was at 15 percent of the level of lumber use in the 1920s and 1930s, but pulpwood use was 27 percent greater than that of solid wood by 1990 and is projected to be 35 percent greater by 2040. Burned residue and black liquor also increased relative to solid wood uses, from 1 Tg in 1910 to 21 Tg in 1990 and will be 31 Tg in 2040. Fuelwood, reaching a low of 3 Tg in 1970, is projected to surpass its 1920 level by 2040 and remain slightly higher than burned residue and black liquor **(Fig. 3).**

TABLE 7. — U.S. net carbon accumulation, emission, net imports, and drain from the atmosphere by year.[a]

	Net carbon flux					
	1990	2000	2010	2020	2030	2040
	(Tg)					
Change in forests, *CIC*	274	174	200	180	170	161
Change in products in use, *P*	26.02	24.99	24.51	25.58	24.27	22.86
Change in landfills, *L*	33.38	32.48	39.37	42.53	46.89	50.74
Wood burning, *WB*	74.38	88.07	96.58	102.83	109.27	118.86
Emitted CO_2, ECO_2	11.43	14.02	14.83	15.77	16.49	16.98
Emitted CH_4 from landfills, ECH_4	0	0.23	0.5	0.61	0.62	0.55
Change in stock of carbon[b]	333.4	231.47	263.88	248.11	241.16	234.6
Net imports of wood products, paper, and paperboard $(I - E)$	2.33	3.26	3.67	3.87	2.84	1.50
Drain from atmosphere, S[c]	331.07	228.21	260.21	244.24	238.32	233.1
Drain from atmosphere in CO_2 equivalents, S_g[d]	331.07	223.61	250.21	232.04	225.92	222.1

[a] Base Case projections.
[b] Change in stock of carbon = $CIC + P + L$.
[c] $S = CIC + P - (I - E) + L$.
[d] $S_g = CIC + P - (I - E) + L - 20(ECH_4)$.

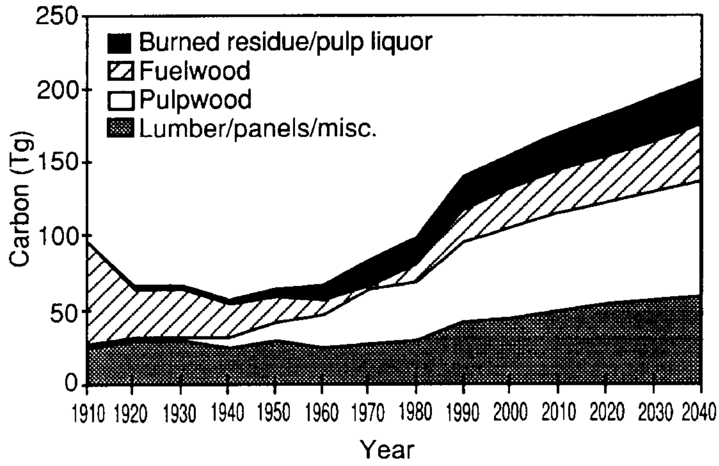

Figure 3. – Distribution of roundwood.

Many more sources of wood carbon are being burned for energy now than in the past. These include roundwood fuelwood; wood and bark residues from sawmills, veneer mills, and pulp mills; black liquor from pulp mills; paper and wood in municipal solid waste; and CH_4 from landfills.

Sanitary landfills have replaced open dumps, which were characterized by open burning and higher decay rates.

Overall, the rate of net additions of carbon to products in use and landfills increased -280 percent between 1970 and 1990 (from 22 to 61 Tg/year). This increase was due in part to the increase in product consumption; roundwood use increased 150 percent between 1970 and 1991, from 35 to 53 × 10^7 m^3 (12.5 to 18.7 × 10^9 $ft.^3$) (6).

The 280 percent increase in rate of net sequestration is also due to a sharp increase in the rate of accumulation of carbon in landfills with the shift from dumps to landfills in the 1970s and 1980s. Net accumulation in dumps or landfills increased from 9.2 Tg/year in 1970 to 33.4 Tg/year in 1990. This increase in net accumulation was due to virtual elimination of open air burning in dumps and a decrease in the rate of decay of wood and paper in landfills compared with that in dumps.

RPA Base Case projections

For the RPA Base Case, the annual rate of carbon additions to forest trees and soil is projected to decline from 274 Tg in 1990 to 161 Tg in 2040 **(Table 7)** (2). This trend reflects a slowdown in the rate of accumulation in the North as forests reach an age of slower tree growth and soil carbon increases, increased management intensity in the South where accumulation is balanced by removals, and reduced harvest on public land in the West along with more intensively managed areas of former old growth (2).

The annual rate of carbon accumulation in landfills or dumps and products is projected to increase from 59 Tg in 1990 to 75 Tg in 2040. This is due entirely to the increasing rate of accumulation in landfills. The net annual addition to products in use actually decreases slightly from 26 Tg in 1990 to 23 Tg in 2040. This decline is due in part to the increasing proportion of wood that is used in paper products, which have a shorter uselife than do solid wood products.

Carbon emissions from burning with energy produced increase as a result of notable increases in burning of black liquor and roundwood (directly from forests) for fuel. Black liquor and roundwood carbon emissions increase from 54 to 92 Tg between 1990 and 2040. Burning of mill residue and other wood or paper waste increases emissions from 20 to 27 Tg during the same period.

Comparison with a previous study

A previous study by Heath et al. (7) made similar historical estimates and projections of wood carbon flux (additions to stocks and emissions) and disposition. They prepared separate historical estimates and separate projections of carbon sequestration, although their projections are based on the same RPA Base Case. Each historical reconstruction required conversions from raw data in board feet of timber and products to cubic volumes. Their projections made exogenous assumptions about the distribution of wood harvested to various end uses (12) while ours used product distribution output of the TAMM/ATLAS and NAPAP models directly.

Their historical estimate of total harvest for 1910 is 20 percent higher than ours but moves to match ours by 1990. Historical estimates could differ, in part, because of different factors used to convert board foot data and different factors used to convert volume to carbon weight. Their projection of harvest is -10 percent lower than our projection of harvest plus net imports by 2040. Projections could differ due to our addition of net imports and to different factors used to convert volume to weight of carbon.

Carbon fluxes. – Our historical estimates and projections of sequestration (or net additions) of carbon into products, landfills, burning with energy, and emissions are shown in **Figure 4.** During the historical period, we estimate lower additions to products, landfills, and higher burning emissions for energy than Heath et al. (7). Our additions to products in 1910 (24 Tg/year) is much lower compared to Heath et al. (65 Tg/year). Their very high additions to products in 1910 results in higher additions to landfills and higher emissions from dumps and landfills in subsequent years. Our estimate of emissions from wood burning for energy is larger in early years and may include more mill residue and black liquor used for fuel. By 1990, their wood burning for energy estimate appears to exclude black liquor from pulping, because they show only 32 percent of harvest going for fuel. We estimated 51 percent, which is in accord with other estimates (15).

Reasons for differences in projections between the two studies are relatively clear. Our projected total for carbon in wood harvested in 2040 is higher than that in Heath et al. due to different conversion and decay factors and our inclusion of net imports. Our projection of additions to products is slightly lower in 2040, 20.6 compared with 22.9 Tg/year. The difference is due to our use of the distribution of wood to primary products and end uses from TAMM/ATLAS and NAPAP compared with their use of exogenous estimates. Our additions to landfills is double their rate, 50.8 compared with 25.3 Tg/year in 2040, due to our very low landfill decay rates for wood and paper. Low decay partially explains our much lower emission rate in 2040, 17.5 compared with 74.1 Tg/year. Our emissions are also lower due to our assumed increase in CH_4 burning for energy. Our wood burning for energy is higher since we include black liquor and CH_4 burning, 119 compared with 68.2 Tg in 2040.

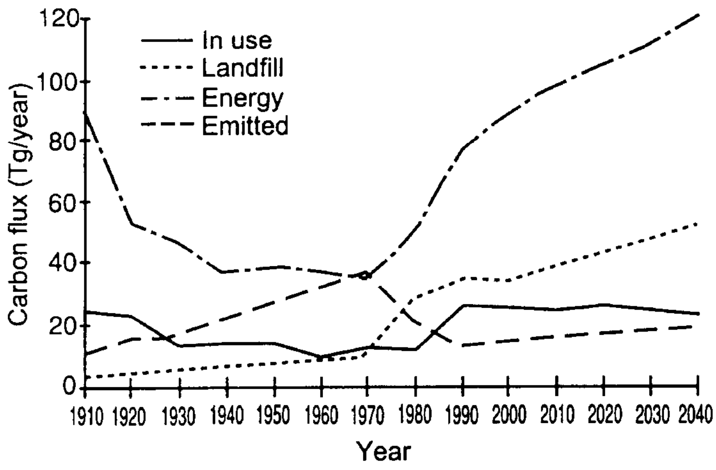

Figure 4. – Carbon fluxes into disposition categories.

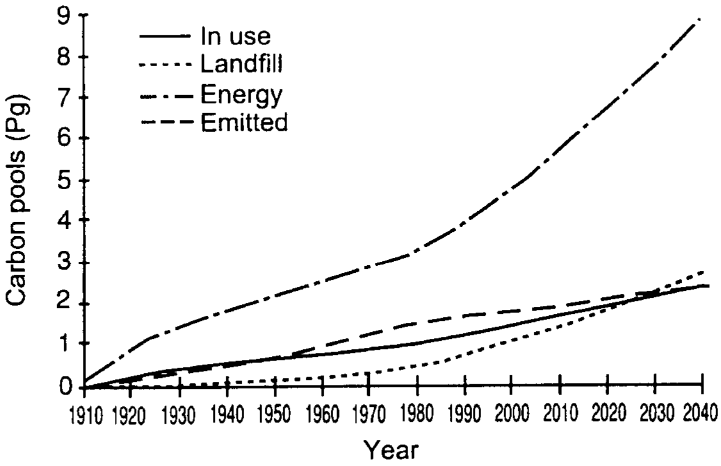

Figure 5. – Carbon pool sizes, 1910 to 2040.

Carbon pools. – Our estimates of the cumulative fate of carbon in the United States since 1910 are shown in **Figure 5.** Heath et al. (7) begin their cumulative estimates in 1900. We compare their estimates to our figures, which begin in 1910. We estimate total carbon use at 7.8 Pg for the period 1910 to 1990; their estimate is 10.7 Pg for 1900 to 1990. We estimate less accumulation in products and landfills (2.1 compared with 3.7 Pg), more in wood burned for energy (4.0 compared with 3.7 Pg), and much less in emissions (1.7 compared with 3.2 Pg) for the same time period.

Our cumulative amount in products and landfills in 1990, 2.7 Pg, is relatively small but significant compared with an estimated 13.8 Pg in trees and 24.7 Pg in soils, forest floor, and understory in the United States in 1987 (1). We project accumulation in products and landfills to increase to 5.3 Pg by 2040.

Total carbon accumulation for just the projection period 1990 to 2040 is 9.0 Pg for this study (which includes net imports) and 8.3 Pg for Heath et al. (7). We estimate for 2040 that 38 percent will have accumulated in products and landfills compared with 27 percent for Heath et al. (7). We estimate 55 percent will have been burned for energy and 9 percent will have been emitted, compared with 35 and 38 percent, respectively, for Heath et al. (7). Our higher accumulation in products and landfills is due primarily to assumed slower decay of wood and paper in landfills. Our higher wood burned for energy is due to counting of black liquor burning for energy and increased burning of CH_4 for energy.

Conclusions

Our projections indicate we have accumulated 2.7 Pg of carbon in the pool of wood and paper products in use and in landfills and dumps in the United States between 1910 and 1990. This is substantial compared with the 1990 pool of carbon in forest trees (13.8 Pg) and in forest soil (24.7 Pg).

In 1990, we were adding to the wood and paper product pools at the rate of 59 Tg per year. This rate is projected to increase to 74 Tg per year by 2040 **(Tables 6 and 7).** If we add sequestration in forest trees and soils, the rate of additions to U.S. stocks is 333 Tg/yr in 1990 and 235 Tg/year by 2040. The annual net drain from the atmosphere to the United States is slightly less than the accumulation in stocks due to net imports supplementing U.S. stocks. Net drain measured in carbon terms is 331 Tg for 1990 and is projected to decline to 233 Tg by 2040. Net drain measured in CO_2 equivalent effect on the atmosphcrc is 331 Tg for 1990 and is projected to decline to 222 Tg by 2040. The total drain from the atmosphere to the United States in 1990 was 24 percent of the 1990 U.S. carbon emissions level of 1,367 Tg.

It is possible to increase the additions to the products and forest pools (or net drain from the atmosphere). Following arc some ways sequestration could be increased if the projected total tonnage of trees harvested remains the same; these key changes could increase net additions to the products pool: 1) shifting product mix to a greater proportion of lignin-containing solid wood, paper, and paperboard products, which decay less in landfills; 2) increasing product recycling; 3) increasing product use-life; and 4) increasing landfill CH_4 burning in place of fossil fuels.

If the tonnage of wood harvested is increased, sequestration increase would be determined by several factors beyond those considered in this analysis: 1) how much *CIC* in the forest would increase in the future as a result of increased harvest today; 2) how much manufacturing emissions would change due to substitution of wood and paper products for nonwood products; and 3) how much emissions may decrease from forest fires due to reduction in fuels available for fires. These are key questions for further study.

Literature Cited

1. Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rept. WO-59. U.S. Dept. of Agri. Washington, D.C.
2. __________ and L.S. Heath. 1995. Carbon changes in U.S. forests. L.A. Joyce, ed. Productivity of America's forests and climate change. Gen. Tech. Rept. RM-271. USDA Forest Serv., Rocky Mountain Forest and Range Expt. Sta., Fort Collins, Colo. pp. 56-70.
3. Clinton, W.J. and A. Gore, Jr. 1993. The climate change action plan. U.S. Government Print. Off., Washington, D.C.
4. Ham, R.K., P.R. Frischel, and M.R. Norman. 1993. Refuse decomposition at a large landfill. *In*: Proc. of the 4th Inter. Landfill Symposium. Sardinia, Italy. CISA, Environmental Sanitary Engineering Centre, Cagliari, Italy. pp. 1046-1054.
5. Haynes, R.W., D.M. Adams, and J.R. Mills. 1995. The 1993 timber assessment update. Gen. Tech. Rept. RM-GTR-259. USDA Forest Serv., Rocky Mountain Forest and Range Expt. Sta., Fort Collins, Colo.
6. Heath, L.S. and R.A. Birdsey. 1993. Carbon trends of productive temperate forests of the coterminous United States. Water, Air, and Soil Pollution 70:279-293.
7. __________, __________, C. Row, and A.J. Plantinga. 1996. Carbon pools and fluxes in U.S. forest products. *In*: Proc. of the NATO Advanced Research Workshop. The role of global forest ecosystems and forest resource management in the global cycle. NATO ASI Series I: Global Environmental Change. Vol. 40. Springer-Verlag, Berlin. pp. 271-278.
8. Ince, P.J. 1994. Recycling and the long-range timber outlook. Background rept., 1993 RPA assessment update. Res. Pap. FPL-RP-534, USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
9. Micales, J.A. and K.E. Skog. 1997. The decomposition of forest products in landfills. International Biodeterioration and Biodegradation 39(2-3):145-158.
10. Nicholson, G.A. 1995. Carbon pools and flows attendant to forest products utilization in the United States. Master's thesis. Univ. of Wisconsin, Madison, Wis.
11. Powell, D.S., J.L. Faulkner, D.R. Darr, Z. Zhu, and D.W. MacCleery. 1993. Forest resources of the United States. 1992. Gen. Tech. Rept. RM-234. USDA Forest Serv., Rocky Mountain Forest and Range Expt. Sta., Fort Collins, Colo.
12. Row, C. and R.B. Phelps. 1996. Wood carbon flows and storage after timber harvest. R.N. Sampson and D. Hair, eds. Forests and global change. Vol. 2: Forest management opportunities for mitigating carbon emissions. American Forests, Washington, D.C. pp. 27-58.
13. Schlamadinger, B. and G. Marland. 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 10(5/6):275-300.
14. United Nations, Climate Change Secretariate. 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Internet address /www.unfccc.de./ p. 23.
15. U.S. Congress Office of Technology Assessment. 1983. Wood use: U.S. competitiveness and technology. OTA-ITE-210. U.S. Congress OTA, Washington, D.C.
16. __________. 1991. Changing by degrees: Steps to reduce greenhouse gases. OTA-0-482. U.S. Congress OTA, Washington, D.C.
17. USDA Forest Service. 1920. Timber depletion, lumber prices, lumber exports and concentration of timber ownership. Rept. on Resolution 311, 66th Congress, 2nd Session. USDA Forest Serv., Washington, D.C.
18. __________. 1933. A national plan for American forestry. Senate Doc. 12, 73rd Congress, 1st Session, Vol. 2. USDA Forest Serv., Washington, D.C.
19. __________. 1948. Forest and national prosperity. USDA Misc. Pub. 668. USDA Forest Serv., Washington, D.C.
20. __________. 1965. Timber trends in the United States. Forest Res. Rept. 17. USDA Forest Serv., Washington, D.C.
21. __________. 1973. The outlook for timber in the United States. Forest Resource Rept. 20. USDA Forest Serv., Washington, D.C.
22. __________. 1982. An analysis of the timber situation in the United States 1952-2030. Forest Resource Rept. 23. USDA Forest Serv., Washington, D.C.
23. __________. 1985. Timber resources for America's future. Forest Resource Rept. 14. USDA Forest Serv., Washington, D.C.
24. __________. 1989. An analysis of the timber situation in the U.S.: 1989-2040. Gen. Tech. Rept. RM-199. USDA Forest Serv., Rocky Mountain Forest and Range Expt. Sta., Fort Collins, Colo.
25. U.S. Environmental Protection Agency. 1994. Characterization of municipal solid waste in the United States 1994 Update. EPA530-R-042. Municipal and Industrial Solid Waste Div., Office of Solid Waste, U.S. Environmental Protection Agency, Washington, D.C. Doc. PB 95-147690. National Tech. Information Serv., Springfield, Va.
26. Wadell, K.L., D.D. Oswald, and D.S. Powell. 1989. Forest statistics of the United States. 1987. Res. Bull. PNW-RB-168, USDA Forest Serv., Portland, Oreg.
27. Wang, Y.S., C.S. Byrd, and C.S. Barlaz. 1994. Anaerobic biodegradability of cellulose and hemicellulose in excavated refuse samples using a biochemical methane potential assay. J. Industrial Microbiol 13: 147-153.