Carbon Sequestration in Wood and Paper Products

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Introduction

Recognition that increasing levels of CO, in the atmosphere will affect the global climate has spurred research into reducing global carbon emissions and increasing carbon sequestration. The main nonhuman sources of atmospheric CO, are animal respiration and decay of biomass (U.S. Congress OTA 1991). However, increases in atmospheric levels are attributed mainly to fossil fuel burning and land use change. While efforts to hold down emissions of CO, continue, increases in CO, 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.

In 1990, U.S. CO, emissions were 1,367 Tg carbon equivalent (Clinton and Gore 1993), where Tg is 1 million metric tons. Wood and paper products play an important role in mitigating these emissions by sequestering carbon. There are currently large stocks of carbon in forests, in wood and paper products in use, and in dumps and landfills. The size of these carbon stocks is increasing. In 1990 approximately 145 Tg of carbon, or 10.6 percent of the level of U.S. emissions was harvested and removed from forests for products. If a substantial portion of this carbon could be prevented from returning to the atmosphere, it could be a notable contribution to mitigating carbon buildup in the atmosphere.

We use the term sequestration to refer to the net sequestration, over a period of time, in a stock 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 sequestration of carbon to forests.

Carbon sequestration to 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 (Schlamadinger and Marland 1996). A worldwide study by Winjum et al. (1998) estimates net flows of carbon out of forests and into products using the two accounting frameworks used in this study—the stock change method, and the atmospheric flow method. They use simplified assumptions to make estimates of net stock changes, and net emissions to the atmosphere by world region and for selected countries. They include estimates of logging residue and assumed decay. Their results, as noted below, are close to ours even though their methods are very different. Other studies focusing on the United States, similar to this one, estimate the actual stocks and flows of carbon from U.S. forests to products in use, to dumps or landfills, and to burning and emissions from decay including reconstruction of historical flows and projections (Heath et al. 1996; Row and Phelps 1996). 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 to products may change.

Our purpose is to show an in-depth method of providing historical estimates and projections of U.S. carbon sequestration to wood and paper products. We compare those estimates to amounts sequestered in U.S. forests (an estimate of carbon stock change in the United States). We also show how amounts used to estimate the net sequestration in products and forests each year may be used to estimate the net removals of carbon from the atmosphere to the United States each year (an estimate of carbon flow to the United States). We discuss how patterns of wood use have changed and will change and how they will influence the pattern and amounts of carbon sequestered.

Methods

Historical data and long-range projections were used to track roundwood and carbon disposition through to end uses such as housing or paper. To track carbon beyond end uses to waste products, we estimated burning, disposal, and decay for waste generated in the process of using primary products, and for rates of product disposal from end uses, decay, and burning.

The scope of the analysis is focused and limited in a number of ways. We track carbon harvested and removed from roundwood harvest sites. The decay and carbon emissions from logging residue is contained in separate estimates we display of net sequestration in forests. We did not estimate the amounts of carbon released due to fossil fuels burned by harvesting equipment, or to power primary or secondary wood and paper products mills, or to make final products using wood (such as housing). We note how much carbon wood and paper products sequester that may offset such emissions. We show estimates of net sequestration in forests; the estimates include all carbon accumulation in trees and soil and all deductions for decay of dead trees including logging residue, and deductions due to emissions from forest fires. We include emissions from all burning of wood residue and discarded wood for energy or incineration and, over time, all regrowth of all trees. Our model projections do not include projections of biomass plantations for energy production. We did not calculate if, over time, the degree to which the effect of harvesting and using wood for fuel increases the growth in forests over the growth that would occur without wood burning, so as to reabsorb the carbon emitted by burning. This is an important question for further research. We estimated the amount of harvested and used carbon and its disposition starting in 1910.

For our historical estimates (post-1909) and projections, we tracked carbon added to, and emitted from, stocks of wood and paper products in the United States. Net sequestration 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. 5.1) (adapted from Row and Phelps 1996). 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 were not considered in this model, since decay and emissions from these residues are modeled as part of the forest ecosystem and included in estimates of change in carbon sequestered in forests (Heath and Birdsey 1993; Birdsey and Heath 1995).

Historical data on wood harvest and end use from 1910 through 1986 are from USDA Forest Service surveys and estimates (USDA Forest Service 1920, 1933, 1948, 1958, 1965, 1973, 1982, 1989; Wadell et al. 1989). Historical wood harvest, from 1910 through 1986, was tracked from primary products, to end uses, to dumps or landfills (Nicholson 1995). Projections of wood harvest and primary product production were made using the models that were used for the 1993 Resource Planning Act (RPA) Assessment Update (Haynes et al. 1995; Ince 1994). 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

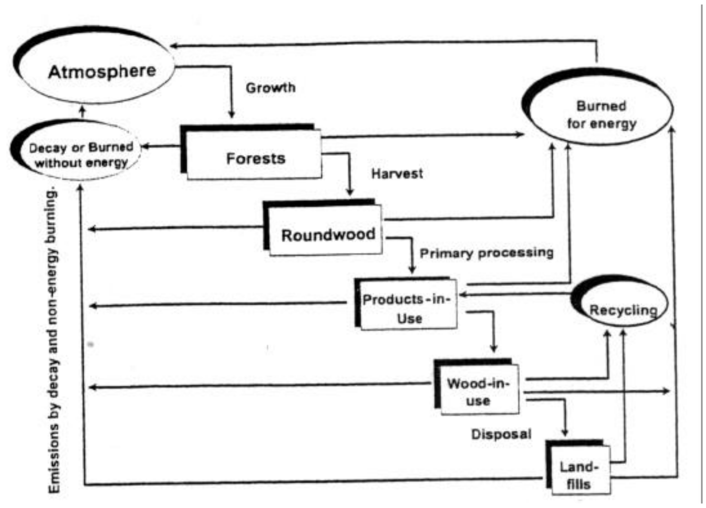

Figure 5.1—Cycling of carbon through wood and paper products.

were processed by the WOODCARB model to make carbon estimates through 2040 for:

- net carbon sequestered in products in use each year (carbon in minus carbon out);
- net carbon sequestered in landfills or dumps each year (carbon in minus carbon out);
- carbon released by burning where useable energy was produced each year; and
- 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, four 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 (see Mills et al. this volume). 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 1910 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 5.1 (Birdsey 1992). 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.

Table 5.1—Carbon per unit of roundwood, by region in kg/m^3 (lb/ft^3).

Region	Softwood factors	Hardwood factors
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)

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 5.2). In most areas, solid wood residues are used almost entirely as raw materials for other processes or are burned for energy. Only a small portion of residues is left to decay or is burned without energy (Powell et al. 1993). Carbon in imports of primary solid wood and paper products is added to each product category, and carbon in exports is deducted.

From Primary Products to End-Use Products and Disposal

Carbon in solid wood products is estimated for nine end-use categories to estimate the time carbon remains sequestered in those products (table 5.3). The TAMM projections are used to divide products into these categories. Pulp and paper products are not tracked to end uses, but the time in use is estimated directly for various primary products. 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% loss for solid wood products and 5% 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 (US EPA 1994).

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 (Row and Phelps, 1996 p. 37). The key parameter in the equation is the half-life for carbon in each end use (table 5.4). 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 modern landfill, the literature indicates that they will stay there indefinitely with almost no decay (Micales and Skog 1997). 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 com-

Table 5.2—Categories of historical and projected wood consumption used to construct estimates of wood carbon use, disposal, and decay.

Historical estimates (1910-1986)	Projections (1986-2040)
Solid wood products and wood mill residue	
Lumber	Hardwood and softwood lumber
Structural paneling	Hardwood and softwood plywood
Nonstructural paneling	Hardwood and softwood in reconstituted panels
Railway ties	Hardwood and softwood miscellaneous products
Miscellaneous products	Hardwood and softwood for roundwood for fuelwood
Roundwood for fuelwood	Hardwood and softwood wood mill residue
Wood and bark mill residue	Hardwood and softwood 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

Table 5.3—End-use categories used to estimate time that 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 5.4—Assumed duration of carbon sequestration in end uses of wood and paper.

End use	Half-life of carbon (years)
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

pletely. Legislation then required that dumps be phased out by 1986. Since then, materials have been placed in landfills. Materials in landfills are periodically covered, which prevents oxygen from entering. For dumps, we estimate that 65 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 geater 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 (Ham et al. 1993; Wang et al. 1994). 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 5.5) (Micales and Skog 1997).

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, is emitted in ~3 years, while half the total CH_4 is emitted in ~20 years (Micales and Skog 1997).

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% of the CH_4 is converted to CO, by micro-organisms 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% level to 58% by 2040.

Calculating Net Removal 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 removal of carbon from the atmosphere through the year 2040. This includes sequestration to forests, products, and landfills, and emissions by burning and decay including emissions from imported products. This section will show why net annual sequestration of carbon in U.S. stocks (forests, products, landfills) is greater than the net removal to the United States from the atmosphere by the amount of net imports.

Gross sequestration 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:

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

Table 5.5—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

where CIC is net sequestration 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. Emissions from forest fires are included in the estimate of net sequestration in forests (CIC). 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 stock of carbon in the atmosphere, and estimate how the forest sector adds to or decreases the size of this stock. We include the emissions from imports in our variables for emissions from the United States. The rate of removal from the atmosphere per year may be expressed as follows (positive terms represent removal from the atmosphere, negative terms represent additions to the atmosphere):

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

where S is net removal of carbon from the atmosphere; G is gross sequestration 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; and 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 removal from the atmosphere to the United States in terms of forest sequestration and emissions, into an equation that expresses the same removal 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 + $WBCH_4$ where WBWOOD is carbon released from burning wood and paper, and $WBCH_4$ is carbon released from burnmg CH_4 released from landfills.

We may express the net sequestration to the stock of products in use (*P*) as the amount harvested minus the removal from products in use plus net imports:

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

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

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

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

By solving equation [4] for SL, substituting in equation [3], and solving for HP, we have

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

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 sequestration to products in use and landfills (*P* and *L*), and emissions from burning and landfill decay (WB, ECO_2, and ECH_4):

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

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 removal from the atmosphere.

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

Equation [7] indicates that net removal from the atmosphere is the sum of net sequestration to carbon in forests, net sequestration to products in use, and net sequestrations to landfills minus net imports.

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

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

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 removal 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 sequestration in one 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 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 Removal to the United States

The greenhouse gas effect of net carbon sequestration by the forest sector is determined in part by whether carbon is emitted to the atmosphere as CO, or as CH_4. A CH_4 molecule is 25 times more effective in trapping heat than a CO_2 molecule (U.S. Congress OTA 1991). 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, molecule has been estimated to be ~21 times greater than the effect of a CO_2 molecule (U.S. Congress OTA 1991). To approximate The greenhouse gas effect of net carbon removal (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,. That is, an atom of carbon in CH_4 results in 21 times more heat trapped than an atom of carbon in CO-,.

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

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

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

About 40% of the carbon from wood and paper decaying in landfills is emitted as CO_2 and about 60% 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 (Micales and Skog 1997). Since half the carbon is emitted

Table 5.6—Estimates of harvested wood carbon sequestered, emitted, and consumed in U.S. annually in Tg (historical reconstruction 1910 to 1980, with projections to 2040 [RPA Base case]).

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
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

as CH_4, converting it to CO_2 could have a notable effect in raising the carbon sequestration 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 total carbon contained in roundwood harvest plus net imports declined between 1910 and 1940 (from 124 to 74 Tg/year) in part as a result of steadily decreasing fuelwood use. After the 1940s the amount of carbon in roundwood doubled by 1995: 74 Tg/year to 150 Tg/year. Total carbon in roundwood and net imports is projected to increase to 210 Tg/year by 2040 as indicated using the 1993 RPA Base case projections for the U.S. forest sector (table 5.6; fig. 5.1).

Since the early 1900s the use of roundwood in primary products [lumber, panels, paper and paperboard, fuel) has shifted from solid wood products and fuelwood, to a mix of products that includes an increasing proportion of paper products and more burning of residue from solid wood products mills and black liquor from pulp mills.

Even though carbon held in solid wood products is projected to double between 1950 and 2040 (30 to 60 Tg), carbon in pulpwood used in paper production will increase 600 percent (to 81 Tg) by 2040. Burning of wood residue and black liquor has 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 use, reaching a low of 3 Tg in 1970, is projected to surpass its 1920 level by 2040 and remain slighly higher than burning of wood residue and black liquor (fig. 5.3).

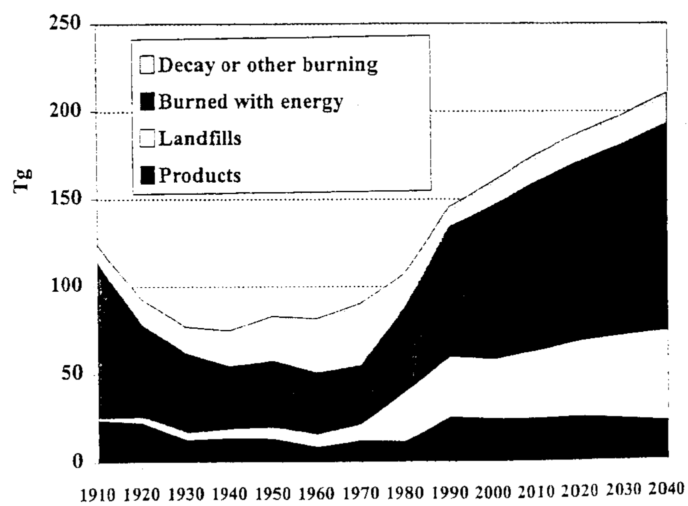

Figure 5.2—Annual net sequestration of harvested wood carbon in products and landfills, and annual emissions from wood burning with energy, and wood and paper decay and other burning in the United States, 1910 to 1993, with projections to 2040.

Table 5.7—United States net carbon accumulation, emission, net Imports, and removal from the atmosphere by year[a].

	Net carbon flux (Tg)					
	1990	2000	2010	2020	2030	2040
Change in forests, CIC	274	189	192	176	166	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	246.47	255.88	244.11	237.16	234.6
Net imports of wood products, paper, and paperboard (*I* - *E*)	2.33	3.26	3.67	3.87	2.84	1.50
Removal from atmosphere, *S*[c]	331.07	243.21	252.21	240.24	234.32	233.1
Removal from atmosphere in CO_2 equivalents, S_g[d]	331.07	238.61	242.21	228.04	221.92	222.1

[a]*Base case projections*
[b]Change in stock of carbon = CIC + *P* + *L*
[c] *S* = CIC + *P* - (*I* - *E*) + *L* (net carbon removal from atmosphere)
[d] S_g = CIC + *P* - (*I* - *E*) + *L* - 20(ECH_4) (net carbon removal from atmosphere in CO_2 equivalents)

Overall, the rate of net sequestration of carbon to products in use and landfills increased -170 percent between 1970 and 1990—from 22 to 59 Tg/year. This net sequestration reflects disposal and decay of products taken out of use, sent to landfills or burned; and decay of wood and paper in landfills. This increase was due in part to the increase in product consumption; roundwood use increased 51 percent between 1970 and 1991, 35 to 53 × 10^7 m^3 (12.5 to 18.7 × 10^9 ft^3) (Heath and Birdsey 1993). It 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.

Using the 1993 RPA Base case projections for the forest products sector, the annual rate of carbon sequestration to forest trees, understory, floor, and soil is projected to decline from 274 Tg in 1990 to 161 Tg in 2040 (table 5.7) (Birdsey and Heath 1995). This trend reflects a slowdown in the rate of accumulation in the North as forests reach an age of slower tree growth and slower increases in soil carbon, and a reduced harvest on public land in the West along with more intensively managed areas of former old growth. It also reflects increased management intensity in the South, where accumulation is balanced by removals (Birdsey and Heath 1995).

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 sequestration 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 use-life than do solid wood products.

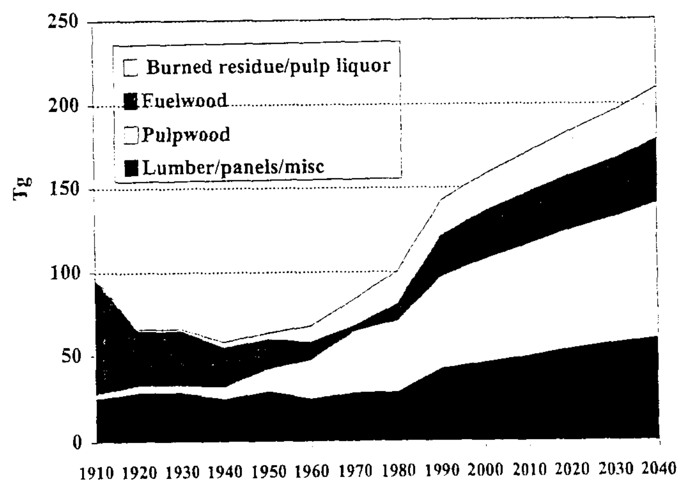

Figure 5.3—Initial product uses of roundwood harvested in the United States, 1910 to 1993, with projections to 2040.

Our estimate of 59 Tg carbon added to landfills, dumps, and products in 1990 is close to the estimate of Winjum et al. (1998) of 57 Tg stored in commodities for five years or more for the United States.

Carbon emissions from burning with energy production are projected to 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. Emissions from burning without energy production and from decay are projected to increase from 11 Tg to 18 Tg between 1990 and 2040. In total carbon, emissions increase from 86 Tg to 137 Tg between 1990 and 2040.

Our estimate of 86 Tg of total emissions in 1990 is identical to the estimate of Winjum et al. (1998) for emissions from all sources in 1990.

In 1990, we were adding carbon to the wood and paper product stocks at the rate of 59 Tg per year. This rate is projected to increase to 74 Tg per year by 2040 (tables 5.6 and 5.7). If we add sequestration to forest trees, understory, floor, and soils, the rate of sequestration to U.S. carbon stocks is 333 Tg/yr in 1990 and 235 Tg/year by 2040.

The annual net removal of carbon from the atmosphere to the United States is slightly less than the accumulation in stocks due to net imports supplementing US. stocks. Net removal of carbon from the atmosphere is 331 Tg for 1990 and is projected to decline to 233 Tg by 2040. Net removal measured in CO_2 equivalent effect on the atmosphere is 331 Tg for 1990 and is projected to decline to 222 Tg by 2040. In 1990, the total carbon removal from the atmosphere to U.S. forests and forest products was 24 percent of the U.S. fossil fuel carbon emissions level of 1,367 Tg (331/1367).

Our estimates of the cumulative fate of carbon in the United States since 1910 (including net imports) are shown in figure 5.5. We estimate total carbon in wood and bark used for products and fuel between 1910 and 1990 at 7.8 Pg (where Pg is 1 billion metric tons). We estimate 2.1 Pg accumulated in products and landfills, 4.0 Pg in wood and bark burned for energy, and 1.7 Pg in emissions. Total accumulation over the projection period, from 1990 to 2040, is 9.0 Pg. Accumulation in products and landfills is projected to be 3.2 Pg between 1990 and 2040 for a total of 5.3 Pg over the period 1910 to 2040.

Conclusions

Our projections indicate we have accumulated 2.1 Pg of carbon in the stock 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 1992 stock of carbon in forest trees (13.8 Pg) and in forest soil (24.3 Pg).

Annual sequestration to product carbon stocks in the United States are slightly geater than annual removal of carbon from the atmosphere. Forest, product, and landfill stocks increased 333 Tg/yr in 1990 while net sequestration to forests, products, and landfills was 331 Tg/yr. This difference is because net sequestration to stocks includes net imports while annual removal from the atmosphere does not. Net removal from the atmosphere may be increased by burning CH_4 from landfills to convert it to CO_2, which has less greenhouse effect.

The choice of accounting method (measuring stock changes, or measuring removals from the atmosphere) could determine how a country would count carbon imports and exports in offsetting greenhouse gas emissions for the purpose of meeting goals under international agreements. This in turn could influence forest and industry management in the U.S. If credit is given for increasing stocks, a country would seek to boost imports and restrain exports. If credit is given for increasing removals from the atmosphere, there would be an emphasis on increasing carbon sequestration in forests and in products from domestic forests that may be aided by increasing exports and restraining imports. There may also be more emphasis on decreasing methane emissions from forest products decay in landfills.

By recognizing what has caused changes in sequestration to carbon stocks in wood products and forests we can identify some ways sequestration can be increased even more. We can increase sequestration to the stock of carbon in products, landfills, and forests while maintaining the same aggregate consumption of wood and paper products by the following actions:

- shifting product mix to a greater proportion of lignin-containing solid wood, paper, and paperboard products, which decay less in landfills;
- increasing product recycling; and
- increasing product use life.

Carbon dioxide equivalent emissions would also be reduced by the actions noted. Emissions would also be reduced by burning more landfill CH_4 in place of fossil fuels.

It may be possible to increase sequestration while increasing product consumption above projected levels but this would be determined by the certain effects of such an increase not assessed in this study:

- How much would annual carbon inventory change in the forest increase in the future as a result of increased harvest today?
- How much would manufacturing emissions change due to substitution of wood and paper for nonwood products?
- How much would emissions from forest fires decrease due to reduction in fuels available for fires?

Acknowledgments

The research for this paper was supported, in part, by a grant from the Environmental Protection Agency, Office of policy, Planning, and Analysis.

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