3. SOURCE REDUCTION AND RECYCLING

This chapter presents estimates of GHG emissions and carbon sequestration resulting from source reduction and recycling of 21 manufactured materials: aluminum cans, steel cans, copper wire, glass, plastic containers (LDPE, HDPE, and PET), corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, carpet, personal computers, clay bricks, concrete, fly ash, and tires. It also presents estimates for s three definitions of mixed paper (broad, residential, and office). Also included in this chapter is a discussion of forest carbon sequestration, an important input in calculating the emission benefits of paper product source reduction and recycling. The chapter is organized as follows:

Section 3.1 Emission benefits of source reduction;

Section 3.2 Emission benefits of recycling;

Section 3.3 Open-loop recycling;

Section 3.4 Source reduction through material substitution;

Section 3.5 Implications and methodology of calculating forest carbon sequestration; and

Section 3.6 Limitations of the analyses presented in this chapter.

To estimate GHG emissions associated with source reduction and recycling (and other MSW management options), EPA used a baseline scenario in which the material is manufactured from the current mix of virgin and recycled inputs, but has not yet been disposed of or recycled. Thus, the baseline for each material already incorporates some emissions from raw materials acquisition and manufacturing using the current mix of virgin and recycled inputs. Using this measurement convention, it follows that source reduction[1] reduces GHG emissions from the raw material acquisition and manufacturing phase of the life cycle for all materials. Moreover, source reduction of paper results in forest carbon sequestration (as discussed in Section 3.5 below).

Manufacturing from recycled inputs generally requires less energy, and thus lower GHG emissions, than manufacturing from virgin inputs. The recycling analysis indicates that recycling reduces GHG emissions for each of the materials studied.

3.1 GHG IMPLICATIONS OF SOURCE REDUCTION

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed above, under the measurement convention used in this analysis, source reduction has (1) negative raw material and manufacturing GHG emissions (i.e., it avoids baseline emissions attributable to current production); (2) forest carbon sequestration benefits in the case of paper products (also treated as negative emissions, as estimated in Section 3.5); and (3) zero waste management GHG emissions. Exhibit 3-1 presents the GHG implications of source reduction.

[1] In this analysis, the values reported for source reduction apply to material lightweighting or extension of a product's useful life. EPA assumes no substitution by another material or product; therefore, EPA assumes no offsetting GHG emissions from another material or product. Thus, the data do not directly indicate GHG effects of source reduction that involves material substitution. Considerations for estimating the GHG effects of material substitution are presented in Section 3.4 below.

In order to compare source reduction to other solid waste management alternatives, EPA compared the GHG reductions from source reduction to the life-cycle GHG emissions of another solid waste management option (e.g., landfilling). This approach enables policymakers to evaluate, on a per-ton basis, the overall difference in GHG emissions between (1) source reducing 1 ton of material, and (2) manufacturing and then managing (postconsumer) 1 ton of the same material. Such comparisons are made in the Executive Summary and in Chapter 8 of this report. For most materials, source reduction has lower GHG emissions than the other waste management options. The most notable exceptions are for aluminum cans and carpet, where source reduction benefits are high, but recycling benefits are higher.

3.2 GHG IMPLICATIONS OF RECYCLING

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste.[2] As with source reduction of paper products, recycling of paper also results in forest carbon sequestration.

Most of the materials considered in this analysis are modeled as being recycled in a closed loop (e.g., newspaper is recycled into new newspaper). However, a few materials are recycled in an open loop, including several paper types (under the general heading of mixed paper)[3], fly ash, carpet, and personal computers (i.e., they are recycled into a product other than themselves); concrete and copper wire are recycled in a quasi-open loop. Mixed paper is included because it is recycled in large quantities and is an important class of scrap material in many recycling programs. However, presenting a single definition of mixed paper is difficult because each mill using recovered paper defines its own supply, which varies with the availability and price of different grades of paper.

For the purpose of this report, EPA identified three definitions for mixed paper: broad, office, and residential. To assist recyclers in determining which definition corresponds most closely to mixed paper streams they manage, the composition of each is presented in Exhibit 3-2. The broad definition of mixed paper includes almost all printing-writing paper, folding boxes, and most paper packaging. Mixed paper from offices includes copier and printer paper, stationary and envelopes, and commercial printing. The typical mix of papers from residential curbside pick-up includes high-grade office paper, magazines, catalogues, commercial printing, folding cartons, and a small amount of old corrugated containers. The broad and residential definitions of mixed paper can be remanufactured via an open loop into recycled boxboard. Mixed paper from offices is typically used to manufacture commercial paper towels.

Fly ash is a byproduct of coal combustion that is used as a cement replacement in concrete. The analysis for carpet is based on nylon broadloom residential carpet and is a composite of several material types, specifically nylon carpet fiber, polypropylene carpet backing, and adhesive of synthetic latex and limestone. It is recycled into carpet pad, carpet backing, and molded auto parts. PCs are also composites, consisting mostly (by weight) of steel, glass, plastics, aluminum, lead, and copper. They are recycled into steel sheet, glass for cathode ray tubes (CRTs), asphalt, aluminum sheet (equivalent to aluminum cans in this analysis), lead bullion, and copper wire. Copper wire itself is not recycled specifically into new copper wire, but is used in the manufacture of copper alloys. Concrete is crushed and used in place of virgin aggregate in the production of new concrete.

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[2] Note that when paper is manufactured from recycled inputs, the amount of paper sludge produced is greater than when paper is made from virgin inputs. This difference is because recycled paper has more short fibers, which must be screened out. EPA made a preliminary estimate of the GHG emissions from paper sludge managed in landfills; the results indicated that net GHG emissions (i.e., CH_4 emissions minus carbon sequestration) were close to zero. Because the emissions are small and highly uncertain, no quantitative estimate is included in this report.

[3] This report also includes estimates for mixed MSW, mixed plastics, mixed organics, and mixed recyclables, i.e., a mixture of the principal paper, metal, and plastic materials that are recycled. These other mixed materials are discussed in Chapter 8.

When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the remanufacturing stage. Consequently, less than 1 ton of new material generally is made from 1 ton of recovered material. Material losses are quantified and translated into loss rates. In this analysis, EPA used estimates of loss rates provided by FAL for steel, dimensional lumber, and medium-density fiberboard (the same materials for which FAL's energy data were used, as described in Chapter 2). ORD provided loss rates for the other materials. These values are shown in Exhibit 3-3

GHG emission reductions associated with remanufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs.

The results of the analysis are shown in Exhibit 3-8. In this exhibit, for each material the differences between manufacture from virgin and recycled inputs for (1) energy-related GHG emissions (both in manufacturing processes and transportation), (2) process nonenergy-related GHG emissions, and (3) forest carbon sequestration are presented. The method of accounting for loss rates yields estimates of GHG emissions on the basis of MTCE per short ton of material recovered for recycling (rather than emissions per ton of material made with recycled inputs).

EPA recognizes that some readers may find it more useful to evaluate recycling in terms of tons of recyclables as marketed (after sorting and processing) rather than tons of materials recovered. To adjust the emission factors reported in Exhibit 3-8 for that purpose, one would scale up the recycled input credits shown in columns "b" and "d" of that exhibit by the ratio of manufacturing loss rate to total loss rate (i.e., Exhibit 3-3 column "c" divided by column "d").

Another way that recycling projects can be measured is in terms of changes in recycled content of products. To evaluate the effects of such projects, one could use the following algorithm:[4]

$$T_{recyc} = T_{prod} \times (RC_p - RC_i)/L \qquad \text{(Eqn. 1)}$$

Where,

T_{recyc} = tons of material recycled, as collected
T_{prod} = tons of the product with recycled content
RC_p = recycled content (in percent) after implementation of the project
RC_i = recycled content (in percent) initially
L = loss rate (from Exhibit 3-3, column "d")

Then, one could use the emission factors in this report directly with the tons of material recycled (as collected) to estimate GHG emissions.

[4] This approach would apply only where the products with recycled content involve the same "recycling loop" as the ones on which the values in this report are based (e.g., aluminum cans are recycled in a closed loop into more aluminum cans).

Exhibit 3-1
GHG Emissions for Source Reduction
(MTCE/Ton of Material Source Reduced)

Material	Avoided GHG Emissions from Raw Materials Acquisition and Manufacturing		Postconsumer	Changes in Forest Carbon Storage		Net Emissions For Current Mix of Inputs	Net Emissions For 100% Virgin Inputs
	For Current Mix of Inputs	For 100% Virgin Inputs		For Current Mix Of Inputs	For 100% Virgin Inputs		
Aluminum Cans	-2.24	-4.27	0.00	0.00	0.00	-2.24	-4.27
Steel Cans	-0.87	-1.01	0.00	0.00	0.00	-0.87	-1.01
Copper Wire	-2.00	-2.02	0.00	0.00	0.00	-2.00	-2.02
Glass	-0.16	-0.18	0.00	0.00	0.00	-0.16	-0.18
HDPE	-0.49	-0.54	0.00	0.00	0.00	-0.49	-0.54
LDPE	-0.62	-0.64	0.00	0.00	0.00	-0.62	-0.64
PET	-0.57	-0.59	0.00	0.00	0.00	-0.57	-0.59
Corrugated Cardboard	-0.24	-0.23	0.00	-1.29	-1.98	-1.52	-2.21
Magazines/Third-class Mail	-0.46	-0.46	0.00	-1.90	-1.98	-2.36	-2.44
Newspaper	-0.52	-0.58	0.00	-0.80	-1.04	-1.33	-1.62
Office Paper	-0.28	-0.28	0.00	-1.90	-1.98	-2.18	-2.26
Phonebooks	-0.68	-0.68	0.00	-1.04	-1.04	-1.72	-1.72
Textbooks	-0.60	-0.60	0.00	-1.90	-1.98	-2.50	-2.58
Dimensional Lumber	-0.05	-0.05	0.00	-0.50	-0.50	-0.55	-0.55
Medium-density Fiberboard	-0.10	-0.10	0.00	-0.50	-0.50	-0.60	-0.60
Carpet	-1.09	-1.09	0.00	0.00	0.00	-1.09	-1.09
Personal Computers	-15.13	-15.13	0.00	0.00	0.00	-15.13	-15.13
Clay Bricks	-0.08	-0.08	0.00	0.00	0.00	-0.08	-0.08
Concrete	NA	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA	NA
Tires	-3.81	-3.81	0.00	0.00	0.00	-3.81	-3.81

Exhibit 3-2
Composition of Mixed Paper Categories (As a Percentage of Total)

Paper Grade	All Paper and Paperboard in MSW [a]	Mixed Paper: Broad Definition [b]	Mixed Paper: Office [c]	Mixed Paper: Single-Family Residential [d]
Uncoated groundwood paper	4.9%	4.9%	7.9%	2.2%
Coated free sheet paper	5.0%	12.0%	13.9%	11.5%
Coated groundwood paper	4.3%	11.5%	30.7%	17.7%
Uncoated free sheet paper	14.3%	37.6%	41.6%	18.4%
Cotton fiber paper	0.1%	0.4%	1.8%	0.2%
Bleached bristols	1.5%	3.9%	4.1%	2.8%
Newspaper	13.3%	2.9%		2.9%
Virgin corrugated boxes	29.6%			12.2%
Recycled corrugated boxes	6.8%			2.8%
Unbleached kraft folding boxes	1.5%	5.7%		4.1%
Bleached kraft folding boxes	2.8%	5.7%		5.8%
Recycled folding boxes	3.0%	7.9%		8.0%
Bleached bags and sacks	0.4%	1.0%		1.6%
Unbleached bags and sacks	2.1%	5.6%		9.0%
Unbleached wrapping paper	0.1%	0.2%		
Converting paper	0.3%			
Special industrial paper	1.3%			
Other paperboard	2.5%			
Paper plates and cups	1.2%			
Tissue, towels	3.9%			
Set-up boxes	0.3%	0.7%		0.6%
Other paper packaging	0.8%			
Totals	100.0%	100.0%	100.0%	100.0%

[a] All grades of paper and paperboard in MSW.
[b] Excludes newspaper, old corrugated containers, tissue produce, paper plates and cups, converting and special industrial papers, nonpackaging paperboard such as album covers and posterboard, and paper labels.
[c] Includes the high-grade papers (ledger and computer printout) as well as stationery, mail, magazines, and manila folders. Could be recovered as "file stock."
[d] Represents a typical collection of mixed paper from a single-family curbside program. Includes printing-writing papers, corrugated boxes, folding cartons, and bags and sacks.
Source: Working papers prepared by Franklin Associates, Ltd., October 1997.

In order to compare GHG emissions from recycling to those attributable to another solid waste management option such as landfilling, EPA compared the total GHG emissions from recycling the material to the GHG emissions from managing the disposal of the same material under another waste management option. The baseline for a given material (which includes GHG emissions from raw materials acquisition and manufacturing for the current mix of virgin and recycled inputs) for both options is the same. Overall, because recycling reduces the amount of energy required to manufacture materials (as compared to manufacture with virgin inputs) and leads to avoided process nonenergy GHG emissions, recycling has lower GHG emissions than all other waste management options except for source reduction.

Exhibit 3-3
Loss Rates For Recovered Materials

(a) Material	(b) Percent of Recovered Materials Retained in the Recovery Stage	(c) Tons of Product Made per Ton of Recycled Inputs In the Manufacturing Stage	(d) (d = b × c) Tons of Product Made Per Ton Recovered Materials	(e) Data Source[a]
Aluminum Cans	100	0.93	0.93	FAL & ORD
Steel Cans	100	0.98	0.98	FAL
Copper Wire	82	0.99	0.81	FAL
Glass	90	0.98	0.88	FAL & ORD
HDPE	90	0.86	0.78	FAL & ORD
LDPE	90	0.86	0.78	FAL & ORD
PET	90	0.86	0.78	FAL & ORD
Corrugated Cardboard	100	0.93	0.93	FAL & ORD
Magazines/Third-class Mail	95	0.71	0.67	FAL & ORD
Newspaper	95	0.94	0.90	FAL & ORD
Office Paper	91	0.66	0.60	FAL & ORD
Phonebooks	95	0.71	0.68	FAL & ORD
Textbooks	95	0.69	0.66	FAL & ORD
Dimensional Lumber	88	0.91	0.80	FAL
Medium-density Fiberboard	88	0.91	0.80	FAL
Tires[b]	90	0.86	0.78	NA

[a] FAL provided data for column (b), while ORD provided data for column (c).
[b] HDPE used as a proxy.

Explanatory notes: The value in column "b" accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column "c" reflects process waste losses at the manufacturing plant or mill. Column "d" is the product of the values in Columns "b" and "c."

3.3 OPEN-LOOP RECYCLING

Unlike most of the materials for which EPA has developed recycling GHG emission factors (e.g., aluminum cans, glass bottles), some materials are assumed to be recycled in an "open loop"—i.e., carpet is recycled into new products other than new carpet. Therefore, the GHG benefits of some material recycling result from the avoided emissions associated with the manufacture of the *secondary* products that the material is recycled into (since the recycling would affect only the production of the secondary products). In applying this method, EPA considered only the GHG benefit for one generation of recycling (i.e., future benefits from recycling the secondary products into additional products were not included). To calculate the GHG benefits of recycling the primary material, EPA compared the difference in emissions associated with manufacturing one ton of each of the secondary products from virgin versus recycled materials, after accounting for losses that occur in the recycling process. The results for each of the secondary products then were weighted by the appropriate material-flow distribution to obtain a composite emission factor for recycling the primary material type. Materials that are recycled in an open-loop fashion within EPA's life-cycle methodology are mixed paper and corrugated cardboard, copper wire, carpet, personal computers, and concrete.

The secondary product resulting from recycling mixed paper is typically boxboard. This use of mixed paper is due to quality constraints related to a broad mixture of paper types that include newsprint, office paper, coated paper, and corrugated paper. The pulp fibers obtained from mixed paper are well suited for lower grade forest product such as cardboard. For the purposes of this methodology, EPA assumed that 100 percent of recycled mixed paper is utilized to produce boxboard. When corrugated cardboard is recycled, it is assumed that 74 percent is used to produce boxboard and the remaining 26 percent is utilized to produce corrugated cardboard. In this sense corrugated cardboard is recycled in a partial open loop. Data for creating the open loops for mixed paper and corrugated cardboard were obtained through consultation with the Recycled Paper Trade Association (RPTA).

Secondary products resulting from carpet recycling include carpet pad, molded products, and carpet backing. Carpet pad is used as a cushion layer between the carpet and the floor, which provides thermal and acoustical insulation, and resilience. Molded products for automobiles are used in a wide range of applications, from air intake assemblies to headrests. The carpet backing produced from recycled carpet is generally used to secure the yarn and provide dimensional stability to commercial carpeting. While current information on this subject is not readily available, the use of recycled material is believed to have become both higher and more widespread. An advantage to recycling carpet into backing is that it uses 100 percent of the materials from the recovered carpet, thereby avoiding a solid waste stream from the recycling process. For details on the recycling life-cycle analysis for carpet, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers.*[5]

When PCs are recycled, they may be recycled into asphalt, steel sheet, lead bullion, CRT glass, copper wire, and aluminum sheet. Recovered plastic can be utilized as a filler component in the production of asphalt for road construction. Steel and aluminum sheet are used to produce a wide range of materials from auto parts to cookware. Recovered CRT glass can be utilized for the production of new CRT screens or processed to recover lead bullion that can be used to produce items such as batteries and x-ray shielding. Copper wire can be utilized in various electrical applications depending on its grade. For details on the recycling life-cycle analysis for personal computers, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Carpet and Personal Computers.*[6]

Copper wire is the most common form of unalloyed copper recycled from a municipal solid waste perspective. Given the very high virgin content of copper wire (due to purity standards), it is likely that recovered copper wire would in most cases go into lower grade copper alloys.[7] Therefore, the most accurate approach would be to determine the energy/emissions associated with the production of smelted copper (ingot), rather than finished copper wire. For details on the recycling life-cycle analysis for copper wire, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Copper Wire.*[8]

When concrete structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate. Doing so reduces the GHG emissions associated with producing concrete using virgin aggregate material. Virgin aggregates, which include crushed stone, gravel, and sand, are used in a wide variety of construction applications, such as road base, fill, and as an ingredient in concrete and asphalt pavement. For details on the recycling life-cycle analysis for concrete, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Clay Brick Reuse and Concrete Recycling.*[9]

Coal-based electricity generation results in the production of significant quantities of coal combustion products (CCPs). Fly ash is a CCP that possesses unique characteristics that allow it to be

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[5] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Go to: http://www.epa.gov/mswclimate, then follow links to Publications → Reports, Papers, and Presentations → This report → Background Documents.
[6] Ibid.
[7] CDA, 2003. *Technical Report: Copper, Brass, Bronze. The U.S. Copper-base Scrap Industry and Its Byproducts.* Copper Development Association, Inc.
[8] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.
[9] Ibid.

utilized as a substitute for Portland cement in making concrete. Through the reuse of fly ash, the GHG emissions associated with the production of Portland cement are avoided. For details on the recycling life-cycle analysis for concrete, please review the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete.*[10]

3.4 SOURCE REDUCTION THROUGH MATERIAL SUBSTITUTION

As noted above, the analysis of source reduction is based on an assumption that source reduction is achieved by practices such as lightweighting, double-sided copying, and material reuse. However, it is also possible to source reduce one type of material by substituting another material. Analyzing the GHG impacts of this type of source reduction becomes more complicated. Essentially, one would need to estimate the *net* GHG impacts of (1) source reduction of the original material, and (2) manufacture of the substitute material and its disposal fate. A quantitative analysis of source reduction with material substitution was beyond the scope of this report because of the large number of materials that could be substituted for the materials analyzed in this report (including composite materials, e.g., a composite of paper and plastic used in juice boxes) and the need for application-specific data. Where both the original material and the substitute material are addressed in this report, however, the GHG impacts of source reduction with material substitution may be estimated.

The estimate would be based on (1) the data provided in this report for the material that is source reduced; (2) the mass substitution rate for the material that is substituted; and (3) data in this report for the material substituted. The mass substitution rate is the number of tons of substitute material used per ton of original material source reduced. Note, however, that in calculating the mass substitution rate, one should account for any difference in the number of times that a product made from the original material is used prior to waste management, compared to the number of times a product made from the substitute material will be used prior to waste management.

To estimate the GHG impacts of source reduction with material substitution (per ton of material source reduced), one should consider the following: a specific baseline scenario, including waste management; an alternative scenario, involving the substitute material and a waste management method; the number of tons of material used in each scenario, using the mass substitution rate; the net GHG emissions for the baseline; the GHG impacts of source reduction of the original material; the GHG impacts of manufacturing the substitute material; and the GHG impacts of waste management for the substitute material. Among other factors, these considerations will allow for a comparison of net GHG emissions from source reduction with material substitution to the baseline.

3.5 FOREST CARBON SEQUESTRATION

As forests are planted and allowed to grow, they absorb atmospheric CO_2 and store it in the form of cellulose and other materials. When the rate of uptake exceeds the rate of release, carbon is said to be *sequestered*. On the other hand, when trees are cleared and processed or burned, carbon is released.

When paper and wood products are recycled or source reduced, trees that would otherwise be harvested are left standing. In the short term, this reduction in harvesting results in a larger quantity of carbon remaining sequestered, because the standing trees continue to store carbon, whereas the manufacture and use of paper and wood products tend to release carbon.[11] In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than would

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[10] Ibid.

[11] The forest carbon inventory in any year equals the carbon inventory the year before, plus net growth, minus harvests, minus decay. Thus, when harvests are reduced, the inventory increases. However when inventories become high relative to the carrying capacity of the land, the rate of growth decreases because net growth (the rate at which growth exceeds decay) declines.

otherwise occur, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly).

In the United States, uptake by forests has long exceeded release, influenced by forest management activities and the reforestation of previously cleared areas. This net sequestration of carbon in forests represents a large and important process. EPA estimated that the annual net CO_2 flux (i.e., the excess of uptake minus release) in U.S. forests was about 213 MMTCE in 2004,[12] offsetting about 8 percent of U.S. energy-related CO_2 emissions. In addition, about 16 million metric tons of carbon was stored in wood products currently in use (e.g., wood in building structures and furniture, paper in books and periodicals). Considering the effect of forest carbon sequestration on U.S. net GHG emissions, it was clear that a thorough examination was warranted for this study.

EPA worked with the U.S. Department of Agriculture Forest Service (USDA-FS) to use models of the U.S. forest sector to estimate the amount of forest carbon sequestration per incremental ton of paper reduced and recycled. These USDA-FS models and data sets are the most thoroughly documented and peer-reviewed models available for characterizing and simulating the species composition, inventory, and growth of forests, and they have been used to analyze GHG mitigation in support of a variety of policy analyses conducted by the Forest Service, so they represent the current state-of-the-art.

EPA used an approach that modeled (1) the effect of incremental recycling on wood harvests, and (2) the change in forest carbon stocks as a function of marginal changes to harvest rates, using the FORCARB II model, and combined the two components to estimate the effect of recycling on forest carbon storage. EPA found that increased recycling of paper products resulted in incremental forest carbon storage of about 0.55 MTCE per ton of paper recovered for mechanical pulp papers and 0.83 MTCE per ton of paper recovered for chemical pulp papers. Papers made from mechanical pulp include newspaper, telephone books, and magazines/third-class mail; papers made from chemical pulp include office paper, corrugated cardboard, and textbooks. The approach to modeling the impact of source reduction and recycling on forest carbon stocks has changed since the last edition of this report was published. The revised approach includes the use of updated USDA-FS models and the differentiation of chemical and mechanical pulp papers.

The USDA-FS models do not directly estimate the effect of source reduction on forest carbon storage. To derive these estimates, EPA evaluated the mix of virgin and recycled inputs used to manufacture each material. As described later, this mix is different for each product. The resulting carbon sequestration rates are 1.04 MTCE per ton for mechanical pulp papers to 1.98 MTCE per ton for chemical pulp papers for 100 percent virgin inputs, and they range from 0.80 to 1.90 MTCE per ton for various paper grades for the current mix of inputs.

3.5.1 Effect of Paper Recovery on Pulpwood Harvest

Several earlier USDA-FS efforts have analyzed the relationship between paper recovery rates and pulpwood harvests, based on data compiled by the American Forest and Paper Association (AF&PA) and the Forest Resources Association (FRA). AF&PA collects information on the mass of recovered paper and wood pulp consumed[13] and paper and paperboard production.[14] FRA publishes information on pulpwood receipts.[15] Using assumptions on the moisture content of pulpwood receipts (as harvested, 50 percent), paper, and paperboard (3 percent), wood pulp consumed (10 percent), and recovered paper consumed (15 percent), Dr. Peter Ince of USDA-FS developed the following relationship:

[12] EPA. 2006. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*. U.S. Environmental Protection Agency, Office of Air and Radiation, Washington, DC. EPA- 430-R-06-002.
[13] AF&PA. 2005. *Wood pulp, recovered paper, pulpwood 25th Annual survey, 2004-2007*. Washington, DC.
[14] AF&PA, 2004. *2004 Statistics—Paper, paperboard and wood pulp*. Washington, DC.
[15] FRA, 2004. *Annual pulpwood statistics summary report, 1999-2003*. Rockville, MD.

$$PWH = X \times (PP - [PR \times \{1 - EX\} \times Y]) \qquad \text{(Eqn. 2)}$$

Where,

PWH = pulpwood harvests at 0 percent moisture content, i.e., ovendry (tons)
PP = paper production at 3 percent moisture content (tons)
PR = paper recovery at 15 percent moisture content (tons)
EX = percent of recovered paper that is exported (%)
X = process efficiency of converting ovendry pulpwood to paper and paperboard at 3 percent moisture content. It is the ratio of finished paper to pulp, and accounts for the portion of paper and paperboard that is water and fillers
Y = process efficiency of converting recovered paper at 15 moisture to paper and paperboard at 3 percent moisture. It is the ratio of recovered paper to finished paper, and accounts for the water in recovered paper.

The values of X and Y are based on process yield estimates provided by John Klungness (Research Chemical Engineer, USDA-FS) and Ken Skog (Project Leader, Timber Demand and Technology Assessment Research, USDA-FS). The value for EX, the export rate, is based on examining total paper recovery and exports over the last 10 years for which data were available (1995-2004). Given that our focus is on the effect of small changes in paper recovery, it is more appropriate to focus on the marginal ratio of exports to paper recovery (rather than the average ratio). Thus, EPA calculated the change in annual exports for the end of the period compared to the beginning (3.23 million tons) and divided this figure by the change in annual paper recovery for the end of the period compared to the beginning (8.1 million tons), yielding a value of 40 percent. EPA used 40 percent as the export rate for both types of paper (mechanical and chemical).

As shown in Exhibit 3-4, the avoided pulpwood harvest is 0.58 tons per ton paper recovered for mechanical pulp papers, and 0.89 tons per ton paper recovered for chemical pulp papers.

Exhibit 3-4
Relationship Between Paper Recovery and Pulpwood Harvest (Values of Eqn. 2 Parameters)

	a Ratio of Pulp to Finished Paper	b (= 1 / a) X = Process Efficiency	c Y = Ratio of Recovered Paper to Finished Paper	d EX	e (= b × c × [1 − d]) Avoided Tons PWH per Ton Paper Recovered
Mechanical Pulp	0.900	1.11	0.875	40%	0.58
Chemical Pulp	0.475	2.11	0.700	40%	0.89

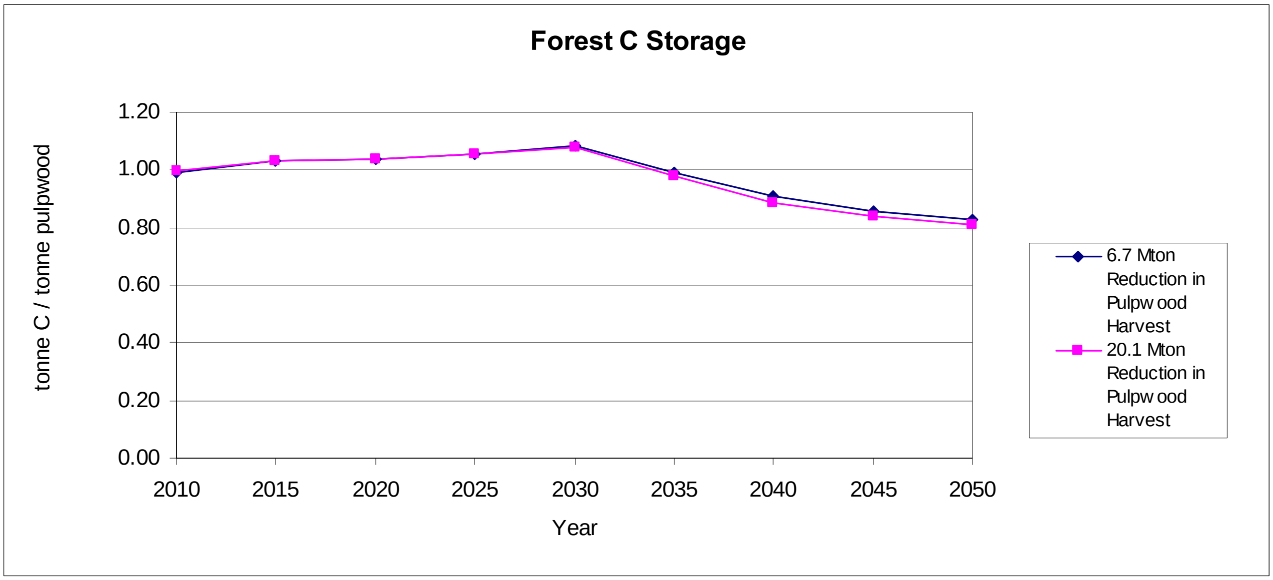
3.5.2 The Effect of Change in Pulpwood Harvest on Forest Carbon—FORCARB II Analysis

FORCARB II simulates the complex, dynamic nature of forest systems, including the interaction of various forest carbon pools, how carbon stocks in those pools change over time, and whether the response of forest carbon is linearly proportional to harvests. To explore these questions, USDA-FS ran two enhanced recycling/reduced pulpwood harvest scenarios in FORCARB II. The base assumptions on pulpwood harvests are derived from NAPAP (North American Pulp and Paper) Model baseline projections developed for the Forest Service 2001 RPA Timber Assessment. The two reduced harvest scenarios involved decreasing pulpwood harvest by 6.7 million tons and 20.2 million tons for the period 2005-2009. Harvests in all other periods were the same as the baseline.

For each scenario, EPA calculated the delta in carbon stocks with respect to the base case—this represents the carbon benefit of reduced harvests associated with recycling. The change in carbon was divided by the incremental tons of pulpwood harvested to yield results in units of MTCE per metric ton pulpwood not harvested, i.e., the carbon storage rate.

As shown in Exhibit 3-5, the carbon storage rate starts at about 0.99 MTCE per metric ton pulpwood in 2010, increases to about 1.08 MTCE per metric ton pulpwood in 2030, and declines with time to about 0.82 MTCE Carbon per metric ton pulpwood in 2050. The exhibit also shows that across the two incremental recovery scenarios, the carbon storage rate (per unit paper recovered) was virtually identical.

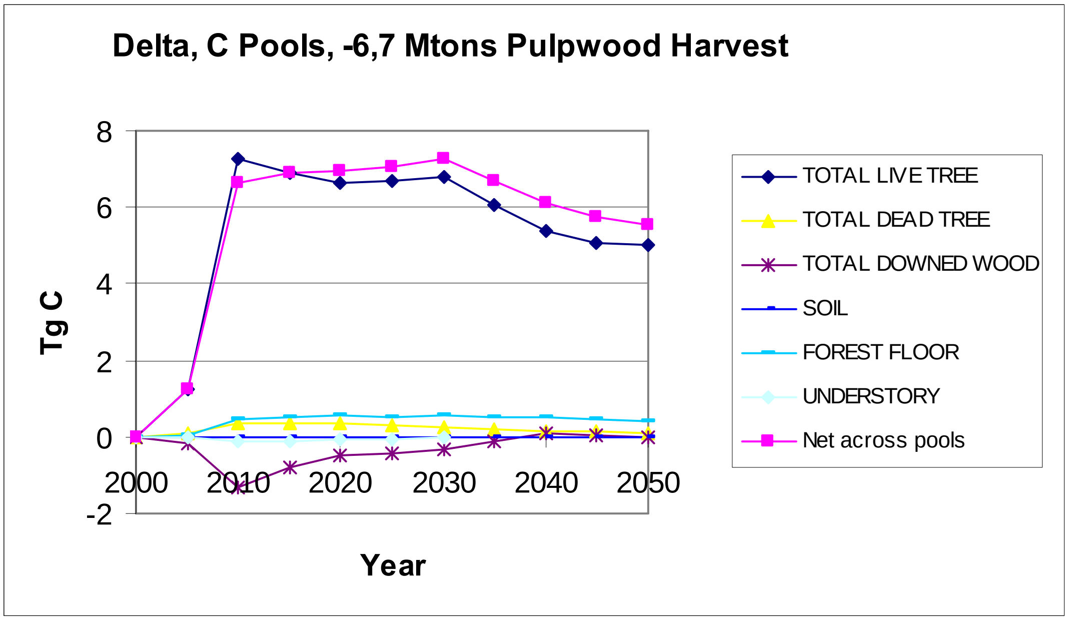
Exhibit 3-5 Increased Forest Carbon Storage per Unit of Reduced Pulpwood Harvest



The use of the FORCARB II model allowed analysis of the timing and magnitude of changes in specific carbon pools within the forest. As shown in Exhibit 3-6, the primary effect of reduced pulpwood harvests was to increase the total live tree pool. This effect was offset to some degree by a decrease in the total downed wood pool. Carbon in the total dead tree, forest floor, and understory pools increased slightly; there was no effect on the soil pool. Most of the deltas peaked in 2010 and moderated somewhat over the next 40 years, though forest floor has more of a lag; the delta peaked in 2030. Both of those pools responded quickly to the change in harvests (which occurred for the 2005-2009 period). It appears that the major driver of the net carbon storage estimate is the time it took for the competing effects in the live tree and total downed wood pools to decline back to the baseline levels; since the total downed wood pool returns to baseline levels more quickly than the Live Tree pool, the net actually increased through 2030.

The FORCARB II results indicate that the effect of paper recycling on carbon storage appears to be persistent (i.e., lasting at least for several decades). EPA chose to use the value for 2020 for use in the emission factors, viz., 1.04 MTCE per metric ton pulpwood. The choice of 2020 represents a delay of about 5 to 15 years with respect to the onset of incremental recycling, long enough to reflect the effects of the recycling program, but lower than the peak effect in 2030. As shown above, the effect is relatively stable over time, so the choice of year does not have a significant effect.

Exhibit 3-6 Change, with respect to baseline, in carbon stocks for FORCARB II pools



For additional details on this methodology and a comparison of the FORCARB II results to those from other analyses, please see the *Background Document on the Effect of Paper Recycling on Forest Carbon*.[16]

3.5.3 Effect of Change in Paper Recovery on Forest Carbon

To estimate the rate of forest carbon change per ton of paper recovery, one can multiply the rate of pulpwood harvest (PWH) per ton of paper recovery (PRC) by the rate of forest carbon (FC) change per ton of pulpwood harvest, as shown below:

For mechanical pulp,

0.58 metric ton PWH per metric ton PRC × 1.04 metric ton FC/metric ton PWH = 0.61 metric ton FC/metric ton PRC

For chemical pulp,

0.89 metric ton PWH per metric ton PRC × 1.04 metric ton FC/metric ton PWH = 0.92 metric ton FC/metric ton PRC

Converting to rates of metric tones forest carbon per short ton of paper (to be consistent with units used throughout this report), the values are 0.55 metric ton FC/ton PRC and 0.83 metric ton FC/ton PRC for mechanical and chemical pulps, respectively. The various paper grades fall into mechanical or chemical pulp categories as follows:

- Mechanical pulp papers—newsprint, telephone books, magazines/third class mail
- Chemical pulp papers—office paper, corrugated cardboard, textbooks

[16] Available at the EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

3.5.4 Effect of Source Reduction on Carbon Stocks

EPA estimated source reduction values under two assumptions: that source reduction displaces only virgin inputs, and that it displaces the current mix of virgin and recycled inputs.[17] For the first assumption, 100 percent virgin inputs, EPA used the process efficiency (X) values described in Section 3.5.1 to calculate the amount of pulpwood harvest reduced per ton of paper source reduction. Those values are 1.11 metric ton PWH per metric ton and 2.11 metric ton PWH per metric ton for mechanical and chemical pulps, respectively (as shown in Exhibit 3-4). Multiplying these values by the rate of forest carbon storage per ton of reduced PWH (1.04 MTCE per ton PWH), and converting to short tons, source reduction of mechanical pulp papers manufactured from 100 percent virgin pulp would increase forest carbon storage by 1.04 MTCE per ton, and for chemical pulp papers, 1.98 MTCE per ton. These values are shown in column (d) of Exhibit 3-7.

The second scenario involves the assumption that source reduction would affect production using the current mix of virgin and recycled inputs. Given that displacing recycled inputs would not influence forest carbon per se, in this scenario the forest carbon effect is only attributable to the proportion of inputs that comprise virgin pulp, as shown in column (e) of Exhibit 3-7. The values in column (f) show the result of multiplying the virgin proportion in the current mix by the forest carbon benefit per ton of 100 percent virgin inputs.

Exhibit 3-7 Forest Carbon Storage from Recycling and Source Reduction

(a) Material	(b) Mechanical (M) or Chemical (C)	(c) Recycling, (MTCE/ton)	(d) Source Reduction, 100% Virgin Inputs (MTCE/ton)	(e) Percent Virgin Inputs in the Current Mix of Inputs	(f) (f = d × e) Source Reduction, Current Mix (MTCE/ton)
Corrugated Cardboard	C	0.83	1.98	65.1%	1.29
Magazines/Third-class Mail	M	0.55	1.04	95.9%	1.00
Newspaper	M	0.55	1.04	77.0%	0.80
Office Paper	C	0.83	1.98	95.9%	1.90
Phonebooks	M	0.55	1.04	100.0%	1.04
Textbooks	C	0.83	1.98	95.9%	1.90

[17] Source reduction may conceivably displace 100 percent virgin inputs if the quantity of paper recovered does not change with source reduction, and all recovered paper is used to make new paper. In that case, if the quantity of paper manufactured is reduced through source reduction, all of the reduction in inputs would come from virgin inputs. It is more likely, however, that source reduction reduces both virgin and recycled inputs. In fact, because source reduction would result in less used product being available to recover, it may have a greater effect on recovered fiber use than on virgin fiber. Thus, even the current mix scenario may represent the high end of the range of effects on forest carbon storage.

3.5.5 Limitations and Uncertainties of the Forest Carbon Analysis

There are several limitations associated with the analysis. The forest product market is very complex, and EPA's simulation of some of the underlying economic relationships that affect the market simplifies some important interactions.

As noted earlier, the results are very sensitive to the assumption on paper exports (i.e., that paper exports comprise a constant proportion of total paper recovery). If all of the recovered paper is exported, none of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest. At the other extreme, if all of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest, the storage factor would be higher. The results are also sensitive to assumptions on the moisture content and the carbon content of pulpwood, pulp, and paper.

Also, this analysis does not consider the effect that decreases in pulpwood harvest may have on the supply curve for sawtimber, which could result in a potential increase in harvests of other wood products. This could result in a smaller reduction in harvest, offsetting some of the carbon storage benefit estimated here. Prestamon and Wear[18] investigated how pulpwood and sawtimber supply would change with changes in prices for each. They estimated that non-industrial private forest and industry may increase sawtimber supply when price for pulpwood increases—and the change is perceived as temporary—although the estimate was not statistically significant. But the sawtimber supply may decrease when pulpwood price increases—and the change is perceived as permanent—but once again the estimate was not statistically significant. Given that the relationship between the price change for pulpwood and supply of sawtimber was not consistent and was often statistically insignificant, there was not compelling evidence to indicate that the omission of this effect is a significant limitation to the analysis.

A related issue is that if there is a decrease in the domestic harvest of pulpwood, it could result in a decrease in the cost of domestic production, which could shift the balance between domestic paper production and imports to meet demand.

Another limitation of the analysis is that it did not account for any potential long-term changes in land use due to a reduction in pulpwood demand, and landowners' choices to change land use from silviculture to other uses. If overall forest area is reduced, this would result in significant loss of carbon stocks. Hardie and Parks[19] developed an area base model for use in Resource Planning Act assessments to help determine factors that influence land area change. They derived a model that estimated the elasticity of forest land area change with respect to pulpwood price change. They estimated the elasticity to be -0.10 but this was not significant at the 10 percent confidence level. This suggests that forest area change would be limited with a modest price change in pulpwood demand.

In summary, there are several limitations and uncertainties associated with the analysis, but they are generally less significant compared to the uncertainty associated with the question of how much paper is exported. Despite the limitations and uncertainties, this analysis provides a reasonable approximation of the effects that increased paper recovery would have on forest carbon stocks.

[18] J.P. Prestamon and D.N. Wear. 2000. *Linking Harvest Choices to Timber Supply*. Forest Science 46 (3): 377-389.

[19] I.W. Hardie and P.J. Parks. 1997. *Land Use with Heterogeneous Land Quality: An Application of an Area Base Model.* American Journal of Agricultural Economics 79:299-310.

3.6 LIMITATIONS

Because the data presented in this chapter were developed earlier in Chapter 2, the limitations discussed in those chapters also apply to the values presented here. Other limitations are as follows:

- There may be GHG impacts from disposal of industrial wastes, particularly paper sludge at paper mills. Because of the complexity of analyzing these second-order effects and the lack of data, EPA did not include them. A screening analysis for paper sludge was performed based on (1) data on sludge generation rates and sludge composition (i.e., percentage of cellulose, hemicellulose, lignin, etc. in sludge),[20] and (2) professional judgment on the CH_4 generation rates for cellulose, etc. The screening analysis indicated that net GHG emissions (CH_4 emissions minus carbon storage) from paper sludge are probably on the order of 0.00 MTCE per ton of paper made from virgin inputs to 0.01 MTCE per ton for recycled inputs. The worst case bounding assumptions indicated maximum possible net GHG emissions ranging from 0.03 to 0.11 MTCE per ton of paper (depending on the type of paper and whether virgin or recycled inputs are used).
- The recycling results are reported in terms of GHG emissions per ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting, and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than estimated here.
- The models used to evaluate forest carbon sequestration and those used to evaluate energy and nonenergy emissions differ in their methods for accounting for loss rates. Although one can directly adjust the emission factors reported here for process emissions so that they apply to tons of materials as marketed (rather than tons as collected), there is no straightforward way to adjust the forest carbon estimate.
- Because the modeling approach assumes closed-loop recycling for all materials except mixed paper, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in the analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all the recycling possibilities for each of the materials analyzed.
- For the purpose of simplicity, EPA assumed that increased recycling does not change overall demand for products. In other words, it was assumed that each incremental ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

[20] ICF Consulting. 1996. Memorandum to EPA Office of Solid Waste, "Methane Generation from Paper Sludge," December.

Exhibit 3-8
GHG Emissions for Recycling (MTCE/Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit[a]: Process Energy	(c) Recycled Input Credit[a]: Transportation Energy	(d) Recycled Input Credit[a]: Process Nonenergy	(e) Forest Carbon Sequestration	(f) (f = b + c + d + e) GHG Reductions From Using Recycled Inputs Instead of Virgin Inputs
Aluminum Cans	-2.92	-0.12	-0.66	0.00	-3.70
Steel Cans	-0.48	-0.01	0.00	0.00	-0.49
Copper Wire	-1.33	-0.02	0.00	0.00	-1.34
Glass	-0.03	0.00	-0.04	0.00	-0.08
HDPE	-0.34	0.00	-0.04	0.00	-0.38
LDPE	-0.42	0.00	-0.04	0.00	-0.46
PET	-0.40	0.00	-0.02	0.00	-0.42
Corrugated Cardboard	0.00	-0.01	0.00	-0.83	-0.85
Magazines/Third-class Mail	0.00	0.00	0.00	-0.83	-0.84
Newspaper	-0.20	-0.01	0.00	-0.55	-0.76
Office Paper	0.06	0.00	0.00	-0.83	-0.78
Phonebooks	-0.17	0.00	0.00	-0.55	-0.72
Textbooks	-0.01	0.00	0.00	-0.83	-0.85
Dimensional Lumber	0.02	0.00	0.00	-0.69	-0.67
Medium-density Fiberboard	0.01	0.00	0.00	-0.69	-0.67
Mixed Paper					
Broad Definition	-0.10	-0.03	0.00	-0.83	-0.96
Residential Definition	-0.10	-0.03	0.00	-0.83	-0.96
Office Paper Definition	-0.08	-0.02	0.00	-0.83	-0.93
Carpet	-1.47	-0.02	-0.47	0.00	-1.96
Personal Computers	-0.41	-0.01	-0.20	0.00	-0.62
Clay Bricks	NA	NA	NA	NA	NA
Concrete	0.00	0.00	0.00	0.00	0.00
Fly Ash	-0.11	0.00	-0.12	0.00	-0.24
Tires[b]	-1.75	0.00	0.00	0.00	-1.75

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
[a] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing, and remanufacturing. Recycling credit is based on closed- and open-loop recycling depending on material.

[b] Recycling of tires, as modeled in this analysis, consists only of retreading the tires.

Explanatory notes for Exhibit 3-8

Columns “b” and “c” show the reduction in process energy GHGs and transportation energy GHGs from making each material from recycled inputs, rather than virgin inputs. The values in columns “b” and “c” are based on (1) the difference in energy-related GHG emissions between making 1 ton of the material from 100 percent virgin inputs and from 100 percent recycled inputs, multiplied by (2) the estimated tons of material manufactured from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing stages. EPA first estimated the values in columns “b” and “c” based on provided by FAL and ORD, as shown in Exhibits 2-3 through 2-6. Note that for two of the mixed paper definitions, the process energy GHG emissions are higher when using recycled inputs than when using virgin inputs (as shown by positive values in column “b”). This difference is because the manufacture of boxboard (the product of open-loop recycling of these types of mixed paper) from virgin inputs uses a high proportion of biomass fuels, and the biogenic CO_2 emissions from biomass fuels are not counted as GHG emissions (see the discussion of biogenic CO_2 emissions in Chapter 1). Still, because of forest carbon sequestration, the net GHG emissions from recycling these two mixed paper definitions are negative.

For column “d, ” which presents the process nonenergy GHG emissions from recycling, EPA used (1) data showing the difference in process nonenergy GHG emissions between making 1 ton of the material from 100 percent virgin inputs and from 100 percent recycled inputs (as shown in the second-to-last column of Exhibits 2-3 and 2-5) multiplied by (2) the estimated amount of material manufactured (in tons) from 1 ton of material recovered, after accounting for loss rates in the recovery and remanufacturing steps.

Next, column “e” shows the estimated forest carbon sequestration from recycling of paper products, as estimated in Section 3.5 The last column (column “f”) sums columns “b” through “e” to show the GHG implications of recycling each material.